THE CLIMATES OF THE UNITED STATES

WARD

Richard H. ~~[illegible]~~

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Boston

AVERAGE ANNUAL PRECIPITATION IN INCHES

O F C A N A D A
GULF OF MEXICO
ATLANTIC OCEAN
West from Greenwich
MINNESOTA
WISCONSIN
IOWA
ILLINOIS
INDIANA
OHIO
PENNSYLVANIA
KENTUCKY
VIRGINIA
NORTH CAROLINA
SOUTH CAROLINA
GEORGIA
ALABAMA
MISSISSIPPI
ARKANSAS
TENNESSEE
New York
Philadelphia
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New Orleans
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Jacksonville
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THE CLIMATES OF THE UNITED STATES

BY

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PREFACE

The purpose of this book is to give a concise and systematic account of the climates of the United States, as complete as is possible within reasonable limits. No volume since Lorin Blodget's "Climatology of the United States" (1857) has attempted to cover this ground. While many of Blodget's generalizations still hold true, his discussion, as well as the data upon which it was based, is from our present point of view incomplete and unsatisfactory. Professor Alfred J. Henry's "Climatology of the United States" (1906), useful as it is, was intended to be little more than a collection of numerical data.

In the present volume I have endeavored to bring together all the essential facts regarding the climates of the United States so that the majority of my readers may not need to seek additional information outside its pages. Those who for any reason may wish to make further study of the subject will find throughout the text abundant references to the literature. It is obvious that a single volume such as this cannot enter into the details of local climates. It must inevitably concern itself with the outstanding features of the larger climatic provinces only, and must often treat even those rather briefly. I trust, however, that my treatment is sufficiently complete to serve all the ordinary purposes of teachers and students of geography, and particularly of such as are giving special attention to climate. I have also had it constantly in mind to make the book useful to medical men, to foresters, to agriculturists, as well as to the general public. I have endeavored to make the presentation vivid by frequent references to the human relations of the various climatic elements and phenomena.

It is my earnest hope that this book may accomplish two things. First, I am anxious that it shall emphasize the very important work already done, both officially by the Weather

Bureau and also by many individual observers and students. Secondly, I cannot help hoping that in spite of all that has been accomplished this volume may stimulate further research along similar lines. The faithful work of the meteorological observer, day after day and year after year, lays the foundation stones of climatology. Upon such records our knowledge of climate must be based. The advancement of our science, however, greatly needs, in addition, the enthusiastic devotion and hard work of intelligent students who will observe and describe local climatic conditions and phenomena and thereby enrich and enliven our knowledge of our country's climates.

This book is the outcome of my study and teaching during the past twenty-five years. The manuscript has been in process of preparation for nearly half that period. At the request of many of my colleagues and students I have from time to time published, as separate articles, much of the subject matter of the following chapters. This was done in order that the material might the sooner become available for use. These articles were all thoroughly revised before being included in the present volume. They were originally published, at various times, in the following scientific journals: *Geographical Review*, *Monthly Weather Review*, *Quarterly Journal of the Royal Meteorological Society*, *Scientific Monthly*, *Proceedings of the American Philosophical Society*, and *Transactions of the American Climatological and Clinical Association*. Permission to reprint these articles, either with or without changes, was granted in each case by the responsible authority.

I gratefully acknowledge my indebtedness to the many officials of the Weather Bureau who have generously helped me. To the Chief of the Weather Bureau, Dr. Charles F. Marvin, to Professors Alfred J. Henry, J. Warren Smith, and C. Fitzhugh Talman, and to Mr. Preston C. Day I am under special obligations. Mr. J. B. Kincer, of the Central Office of the Weather Bureau, has very kindly helped me with the chapter on climate and crops, and Mr. M. B. Summers, for many years Weather Bureau official at Juneau, Alaska, has performed a similar valued service in connection with my discussion of the climates of Alaska. Professors A. E. Douglass and Ellsworth Huntington

have been good enough to see that my own statements concerning the non-instrumental evidence of variations in rainfall shall more accurately present their views. Professor J. E. Church, Jr., of the University of Nevada, has assisted me in the discussion of the measurement of snowfall. I have naturally drawn freely upon the sections on climate of the *Atlas of American Agriculture.* Many of the maps in the present volume have been redrawn from those in that publication, and numerous statements contained in its text have been incorporated into my own discussions. In this atlas we have for the first time a consistent set of climatic maps based on observations most of which cover the same period of time, or which have been reduced to the same period. It is therefore inevitable that anyone who deals with the climatology of the United States should make free use of this excellent new material which will for years to come remain standard and authoritative. In connection with my use of this atlas I am indebted for many courtesies to Dr. O. E. Baker of the United States Department of Agriculture.

Professor William Morris Davis has been a constant inspiration to me throughout my professional career. From Professor Davis I have never failed to receive interested and helpful criticism and encouragement during more than thirty-five years of association and friendship with him. Julius von Hann, whose death in 1921 removed the world's leading climatologist, was for many years a generous and helpful correspondent. His writings and his advice have been of incalculable benefit to me.

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NOTE: Acknowledgment of all figures that are not original is made in the text or footnotes.

THE CLIMATES OF THE UNITED STATES

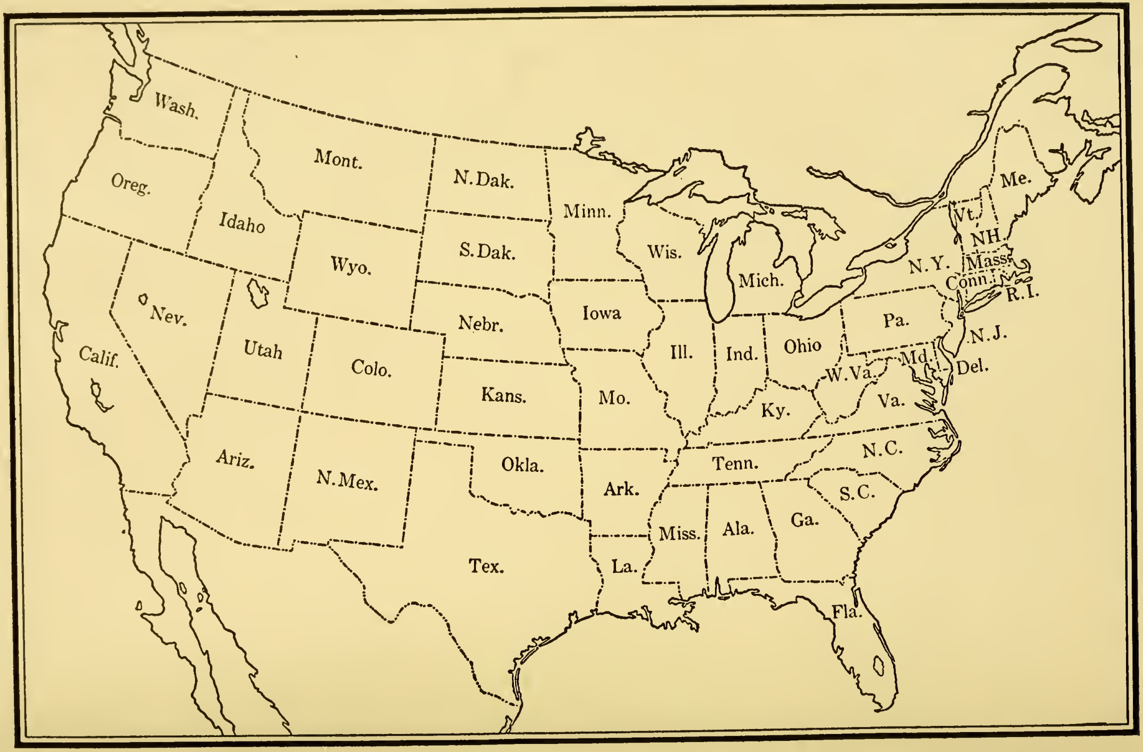

FIG. 1. Identification Map

CHAPTER I

HISTORICAL DEVELOPMENT OF CLIMATOLOGICAL WORK IN THE UNITED STATES

THE BASIS OF CLIMATOLOGICAL STUDY · EARLY INDIVIDUAL OBSERVATIONS IN THE UNITED STATES · THE BEGINNINGS OF ORGANIZED METEOROLOGICAL OBSERVATIONS · THE NATIONAL WEATHER SERVICE · THE INCREASING EMPHASIS UPON CLIMATOLOGY · THE AVAILABLE STANDARD PUBLICATIONS

The Basis of Climatological Study. Climatology deals with the same group of atmospheric conditions or *elements* as those with which meteorology is concerned. The characteristics of each of these *climatic elements* are set forth, and a full description of a climate is given, by means of a standard series of numerical values. These should be based on systematic and long-continued meteorological records, carefully corrected, compared, and summarized by well-known methods, and tabulated in standard form.

Early Individual Observations in the United States. Every person who carefully records an extended series of accurate meteorological observations therefore potentially contributes to a better knowledge of the climatology of his country. American climatology really owes its beginnings to the pioneers who, alone and with inadequate facilities and equipment, faithfully kept their daily records in the earlier years of the country's history. Names which may well be remembered are those of the Reverend John Campanius, who in 1644–1645, at the Swedes' Fort, near Wilmington, Delaware, kept what is believed to have been the first regular record of the weather on the North American continent; of the Honorable Paul Dudley, Chief Justice of Massachusetts, who kept a meteorological record at Boston, Massachusetts, in 1729–1730; of Dr. John Lining, who began thermometer records at Charleston, South

Carolina, in 1730 and maintained a more extended series of observations from 1738 to 1750; of Professor John Winthrop of Harvard College, who, from 1742 to 1778, kept regular weather records at Cambridge, Massachusetts.[1] It is not unworthy of mention that Thomas Jefferson at Monticello, Virginia, and James Madison at Williamsburg, Virginia, "maintained a series of contemporaneous observations" during the period 1772–1777 and "showed that the climatic peculiarities of those two places harmonize completely."[2] And Benjamin Franklin, also, scientifically best known because of his famous kite experiment, kept records of weather and of water temperatures during his homeward voyage from England.

The Beginnings of Organized Meteorological Observations. The early pioneers were enthusiastic observers and did painstaking work, but their efforts were scattered and could not contribute to the development of scientific climatology. Coöperation and coördination of effort were essential, and these involved organization and a central control. Thus it gradually came about that the local observers became part of a system; and uniformity of work, on an increasing scale, replaced the more or less haphazard and irregular observations of the earlier period. The first series of meteorological observations organized under national control was inaugurated by the medical department of the army in 1819. By an order of the Surgeon-General, dated July, 1818, it became the duty of each hospital surgeon "to keep a diary of the weather," and these "diaries" have been continued at many army medical posts ever since, although the records have since 1890 been turned over to the Weather Bureau. "Meteorological Registers," embodying the results of these observations, were issued at various times, and in 1860 the Surgeon-General published a report which brought the results down to date, thus covering about forty

[1] Cleveland Abbe, "A Chronological Outline of the History of Meteorology in the United States of North America," *M. W. R.*, Vol. 37 (1909), pp. 87–89, 146–149, 178–180, 252–253. A. J. Henry, "Early Individual Observers in the United States," *U. S. Weather Bur. Bull. 11*, Part II (1895), pp. 291–302. B. M. Varney, "Early Meteorology at Harvard College," *M. W. R.*, Vol. 36 (1908), pp. 140–142.

[2] Alexander McAdie, "Simultaneous Meteorological Observations in the United States during the Eighteenth Century," *U. S. Weather Bur. Bull. 11*, Part II (1895), pp. 303–304.

years.[1] In 1842 a volume entitled "The Climate of the United States and its Endemic Influences," by Dr. Samuel Forry, was based upon the data collected by the army medical department.

The Smithsonian Institution, under its first secretary, Professor Joseph Henry, inaugurated a fairly extended system of observations in 1849. This was continued for twenty-five years, when (in 1874) the meteorological work of the Institution was formally transferred to the War Department.[2] The number of observers who coöperated in these observations varied from 100 to about 350. The data thus collected were utilized as the basis of several important studies, those of most direct climatological interest being two monographs by Charles A. Schott, both of which appeared in the *Smithsonian Contributions to Knowledge*.[3]

An early volume which may well be called "a real treasure house of the meteorological observations made before about 1850" is Lorin Blodget's "Climatology of the United States."[4] Out of the confused mass of scattering observations which had been accumulating from different sources at the Smithsonian Institution, at the office of the Surgeon-General, and from "gentlemen at distant points distributed over the country," Blodget brought, so far as was then possible, both order and accuracy. His book is still a valuable summary of many of the outstanding facts of American climates.

[1] Major Charles Smart, U. S. A., "The Connection of the Army Medical Department with the Development of Meteorology in the United States," ibid., pp. 207–216.

[2] S. P. Langley, "The Meteorological Work of the Smithsonian Institution," ibid., pp. 216–220.

[3] C. A. Schott, "Tables and Results of the Precipitation in Rain and Snow, in the United States; and at Some Stations in Adjacent Parts of North America and in Central and South America," *Smithson. Contrib. to Knowl., No. 222*, 1872; 2d ed., *No. 353*, 1881. Idem, "Tables, Distribution and Variation of the Atmospheric Temperature in the United States and Some Adjacent Parts of America," ibid., *No. 277*, 1876.

[4] Lorin Blodget, "Climatology of the United States, and of the Temperate Latitudes of the North American Continent: Embracing a Full Comparison of these with the Climatology of the Temperate Latitudes of Europe and Asia, and especially in Regard to Agriculture, Sanitary Investigations, and Engineering, with Isothermal and Rain-Charts for each Season, the extreme Months, and the Year. Including a Summary of the Statistics of Meteorological Observations in the United States, condensed from Recent Scientific and Official Publications," Philadelphia, 1857, xvi + 536 pages. See also R. DeC. Ward, "Lorin Blodget's 'Climatology of the United States,' An Appreciation," *M. W. R.*, Vol. 42 (1914), pp. 23–27.

After the medical department of the army had begun its meteorological work and before the Smithsonian Institution had inaugurated its system of observations, the Regents of the University of New York had established a local series of meteorological observations in that state (1826–1850), and the Franklin Institute and the American Philosophical Society of Philadelphia, with the aid of the state of Pennsylvania, had coöperated in establishing a number of meteorological stations in Pennsylvania (1837). These were the beginnings of local state weather services, all of which later became absorbed in the Federal weather service.[1]

The National Weather Service. The actual establishment of a general national weather service came in 1870, in a joint resolution of Congress (approved February 9, 1870), providing for the taking of meteorological observations at military posts and at other points and for giving notice of the approach and force of storms. This important undertaking was put in charge of the Chief Signal Officer of the army, and there remained until July 1, 1890, when it was transferred to the Weather Bureau of the Department of Agriculture.[2]

The Increasing Emphasis upon Climatology. In the early days of the Signal Service emphasis was naturally chiefly laid upon the immediate problems connected with storm warnings and weather forecasting. This was strictly meteorological work. Gradually, however, as meteorological data began to accumulate and as agricultural interests became more important, more and more emphasis was laid upon the climatological applications of the national weather service work. The voluntary observers in the different states and territories were more systematically organized, a comprehensive and uniform scheme for taking observations was gradually developed, and regular climatological summaries were published. Thus, after many decades of the slow accumulation of meteorological records,

[1] H. H. C. Dunwoody, "State Weather Service Organizations," *U. S. Weather Bur. Bull. 11*, Part II (1895), pp. 285–291.

[2] Cleveland Abbe, "The Meteorological Work of the United States Signal Service," ibid., pp. 232–285. Other papers on the development of meteorology in the United States are included in this same *Bulletin*.

the stage has been reached when the essential facts concerning the climatology of the United States, although not yet ascertained as completely and as accurately as is desirable or as will eventually be possible, can nevertheless be presented in such a way as to meet all ordinary requirements. It is only in the last two or three decades that the observers have been fairly well distributed over the country, that their number has been reasonably adequate, and that their observations have been made on a comprehensive and uniform plan. Hence the period covered by the most complete and reliable climatological records is in most cases a relatively short one.

The Available Standard Publications. The standard general descriptive and statistical volume has for some years been A. J. Henry's "Climatology of the United States."[1] The first eighty-four pages deal with the larger features of the climates of the United States. For each state there is also given a brief discussion of its essential climatic characteristics, followed by a summary of the more important climatic data for representative stations. The latter are grouped by counties and are alphabetically arranged in the index, so that reference is easy. The statistics as a rule cover the years 1870–1903, but in a good many cases the period is shorter.[2]

Another valuable body of statistical data is contained in the *Summary of the Climatological Data for the United States by Sections.*[3] A very large mass of numerical material, especially in regard to rainfall, is here brought together in a convenient form for ready reference, and many of the ordinary questions concerning climatic conditions in the United States which are daily asked by hundreds of persons here find a ready answer. The country is divided into one hundred and six climatological sections. For practically every section there is a

[1] *U. S. Weather Bur. Bull. Q*, 1906.

[2] The data are not homogeneous and are not reduced to the same period. The temperatures are given in whole degrees (F.) only.

[3] *U. S. Weather Bur. Bull. W* (1914 and later dates), 2 vols. The first volume covers the country west of the Mississippi; the second contains the data for stations east of the Mississippi. Price, 5 cents for each section; 10 cents for any three sections; $3 for entire set unbound. To be obtained from the Superintendent of Documents, Government Printing Office, Washington, D. C.

well-considered brief summary of the topographic and climatic features. Then follows a compact digest of the most essential climatological material which has accumulated during the last half-century, the precipitation data being given in full not alone by averages for the whole period but, for the most important data, by individual months and years as well. Monthly and annual amounts of precipitation, monthly and seasonal snowfall data, averages and extremes of temperature, frost data, wind velocity and direction, and other information are presented for each station which has a record long enough to give a fairly accurate picture of the actual climatic conditions. For each section there is a full page of diagrams showing the comparative monthly distribution of precipitation at selected stations. These diagrams illustrate very clearly the occurrence of wet and dry seasons and the local variations in rainfall due to topography and general environment. One of the most useful features is a contoured topographic map of each section, showing the location of the stations and of the principal rivers. The period covered by the data varies. Reprints are issued from time to time, bringing the observations down to the latest dates possible. Several important additions to the tables have also been made in these reprints. Further, the *Annual Reports of the Chief of the Weather Bureau* contain the continuation of these data year by year for Weather Bureau stations.[1]

Detailed climatological data covering all the stations maintained by volunteer coöperative observers as well as the regular Weather Bureau stations are collected and published in the monthly and annual reports of *Climatological Data,*[2] issued at the so-called Section Centers, each section as a rule corresponding to a state. Further, the *Monthly Weather Review* contains a summary of weather conditions; the usual standard climatological data for regular Weather Bureau stations and a series of charts showing the departure of the mean monthly

[1] This is a congressional document. It may usually be obtained on application to members of Congress.

[2] *Climatological Data,* a monthly volume in one cover, containing data for all the sections except Alaska, Hawaii, and Porto Rico, is issued at 35 cents a copy.

temperature from the normal; the total monthly precipitation; the percentage of clear sky; the sea-level isobars, isotherms, and prevailing winds; the total snowfall (in winter months); etc. The *Review* also contains many papers on local and general climatology. Supplements to the *Review* are issued from time to time, containing more extended discussions of various matters of meteorological or climatological importance.[1]

In addition to the foregoing standard statistical publications, there is a large and rapidly increasing number of reports of varying degrees of importance on the climates of different states or cities. Most of these discussions have appeared in the publications of state or of local scientific and other organizations and are therefore widely scattered. No complete list of these papers is available. Anyone who wishes to secure information in regard to the published discussions of any particular state or district should write to the Chief of the Weather Bureau (Washington, D. C.) or to the officials in charge of the various Section Centers. Among the most important of these publications the volumes of O. L. Fassig on the climate and weather of Baltimore, and of H. J. Cox and J. H. Armington on the weather and climate of Chicago, deserve special mention because of their completeness.[2]

Many publications, both official and other, contain charts. A special set of climatic charts has been issued by the Weather Bureau.[3] The section on climate of the new *Atlas of American*

Subscription for twelve monthly copies and the annual summary, $4. Reprints for single sections, 5 cents each; for one year, 50 cents. To be obtained from the Superintendent of Documents, Government Printing Office, Washington, D. C.

[1] *Monthly Weather Review*. Copies may be obtained from the Superintendent of Documents, as above, at 15 cents each. The subscription price per volume is $1.50. Subscription to the *Monthly Weather Review* does not include the *Supplements*, which are issued irregularly and at a fixed price. Abstracts of these *Supplements* are published in the *Review*, together with a statement as to the price in each case.

[2] O. L. Fassig, "The Climate and Weather of Baltimore," *Maryland Weather Service*, Vol. II (1907); H. J. Cox and J. H. Armington, "The Weather and Climate of Chicago," *Geogr. Soc. of Chicago, Bull. No. 4*, 1914.

[3] Climatic Charts of the United States, *U. S. Weather Bur.* Eleven charts, 10 x 16 inches, 50 cents per set. Separate charts, 5 cents each.

For additional titles reference should be made to the price list of government publications on Weather, Astronomy, and Meteorology (Price List 48), which may be secured from the Superintendent of Documents, Government Printing Office,

Agriculture contains the latest and best statistical and cartographic information on the subjects with which it deals. Frequent reference will be made to this important publication in the discussions which follow.

A valuable series of papers on various phases of medical climatology has appeared in the *Transactions of the American Climatological* (now *American Climatological and Clinical*) *Association.* On the general subject of medical climatology in the United States reference should be made to "Climatology and the Principles of Climatotherapy" by F. Parkes Weber, M.D., with the collaboration for America of Guy Hinsdale, M.D.[1]

Washington, D. C., and to the latest list of "Publications of the U. S. Weather Bureau Available for Distribution," which may be secured from the Chief of the United States Weather Bureau, Washington, D. C. Publications in the latter list are free.

Many references to publications of earlier dates will be found in the following: "Bibliography of Meteorology. A Classed Catalogue of the Printed Literature of Meteorology from the Origin of Printing to the Close of 1881; with a Supplement to the Close of 1889, and an Author Index." Prepared under the direction of Brigadier General A. W. Greely, Chief Signal Officer, U.S.A. Edited by Oliver L. Fassig. Washington, D.C., 1889, 1891. In four parts: Part I, Temperature; Part II, Moisture; Part III, Winds; Part IV, Storms.

[1] Vols. III and IV of "A System of Physiologic Therapeutics," edited by S. S. Cohen. Philadelphia, 1901, pp. 336, 420. Volume IV is devoted to an account of American health resorts.

CHAPTER II

THE MAJOR CLIMATIC CONTROLS

CLIMATE IN GENERAL · THE MAJOR CONTROLS OF CLIMATE · LATITUDE · LAND AND WATER · MOUNTAIN BARRIERS · ALTITUDE · PREVAILING WINDS · OCEAN CURRENTS · STORM CONTROL

Climate in General. Climate is most briefly defined as *average weather*. Means or averages may, however, be made up of widely differing values of the elements which go into them. Therefore a satisfactory presentation of climate must include more than mere averages. It should also take account of regular and irregular daily, monthly, and annual changes, and of the departures, mean and extreme, from the average conditions which may occur at the same place in the course of time. This extension of the definition of climate is especially important in any region where irregular cyclonic variations of weather conditions are frequent, as in the so-called "temperate" latitudes of both the Northern Hemisphere and the Southern. Therefore, just as weather types change from day to day and from season to season under varying controls, so climate is the resultant of many variables. One climate differs from another because of a different combination of these controls. While it is a relatively simple matter to enumerate the factors which combine to produce any given climate, it is difficult, if not impossible, to determine quantitatively the relative importance of the various controls, so intimately are they connected and so complex are their effects.

The Major Controls of Climate. The sun is obviously the fundamental control of climate. The general distribution of temperature over the earth's surface, as well as the diurnal and seasonal changes, depend upon variations in the intensity and in the duration of sunshine. This solar control of climate is commonly known as the control by (1) latitude, and stands

first. If the sun alone were concerned, all places on the same latitude circle would have the same climate, for the intensity and amount of sunshine depend upon the angle of incidence of the sun's rays and upon the length of the day, and both of these depend on latitude.[1]

Such a condition is very decidedly modified by the distribution and influence of (2) land and water; (3) mountain barriers; (4) altitude; (5) prevailing winds; (6) ocean currents, and (7) storms. The reaction of the physical features and conditions of the earth's surface upon the atmosphere results in what is termed *physical climate*. According to the dominant control in each case we may have *continental*, *marine*, or *mountain* climates. In the first, land is the essential control; in the second, the ocean; in the third, altitude. An extreme development of the continental type is a *desert* climate. A transitional type, between continental and marine, is a *littoral* climate.[2] The relative importance of the above-mentioned major controls of climate, and the types of climate which result from their interaction, inevitably vary greatly in different places according to the geographical location, and the physical, topographic, atmospheric, and other conditions peculiar to each district. For the United States the outstanding facts regarding each of these major controls are here briefly stated.

Latitude. The difference in latitude between the northern and southern portions of the United States is the fundamental control which determines the important fact that the mean annual, the seasonal, and the monthly isotherms as a whole show prevailingly lower temperatures in the north than in the south.[3] Yet these isotherms do not run east and west across the continent, as they would were latitude the sole control. Their deflections from the latitude lines show the influence of other controls, such as land and water, mountains, ocean currents, winds. If winds have a free sweep across a country, they inevitably wipe out climatic boundaries. They import

[1] *Solar climate* is the term for a climate which is controlled solely by the amount of solar radiation which any place receives by reason of its latitude.

[2] For fuller details regarding the characteristics of these different types of climate see R. DeC. Ward's "Climate considered especially in Relation to Man" (2d ed.), 1918.

[3] See Chapter V.

heat and cold from a distance, and often to a marked degree — sometimes even completely — nullify the effects of latitude. It is therefore impossible to give any quantitative estimate of the importance of latitude as a climatic control; but sunshine, here expressed by the term *latitude*, must be placed first in the list of major controls.

Land and Water. The influence of latitude may be wholly overcome by the effects of land and water. Land and water are fundamentally different in their behavior regarding absorption and radiation. Land areas and the air over them warm and cool readily and to a considerable degree; water areas and the air over them warm and cool slowly and relatively little. In the same latitudes, disregarding possible permanent differences in cloudiness, the insolation received at the surface on land and water surfaces is much the same. The differences in absorptive power of different land areas, also of water surfaces in various conditions of disturbance or quiescence, may be quite noticeable. However, the absorbed heat penetrates to but slight depths in the case of land surfaces, and because of the low specific heat of earth materials, especially when dry, the surface temperature of land areas increases greatly under insolation. Since the coefficient of radiation is comparable with that of absorption, the loss of temperature under cooling conditions is considerable. In contrast to this, the heat absorbed by water surfaces may penetrate to considerable depths, a fact which, coupled with the very high specific heat of water, causes but slight change of temperature under either heating or cooling conditions.

The larger continental areas of the middle and higher latitudes therefore have great seasonal fluctuations in temperature. They are distinctly radical in their tendencies. They absorb much heat, but part with it readily. The oceans, on the other hand, are conservative. They warm but little during the day and in summer. They cool but little during the night and in winter. They take in little heat, and part with it reluctantly. Conservatism in temperature is a distinctive feature of marine climates. Another essential difference between oceans and continents is that the waters of the oceans are almost

constantly in motion, whereas the lands are stationary. The temperatures of the oceans in higher and in lower latitudes thus tend to become equalized. This process results in keeping the waters near the equator from becoming as warm, and those away from the equator from becoming as cold, as they otherwise would be. The land masses, on the other hand, have to take the temperature appropriate to their latitude and season. It follows that North America as a whole is cooler in winter and warmer in summer than the adjacent oceans in similar latitudes. This is clearly shown on the isothermal charts for January and July.[1] In the average for the year the lower latitudes of North America are warmer than the adjacent oceans in similar latitudes, and the higher latitudes are colder. It is obvious that when an isotherm crosses both land and water areas, it is likely to be deflected poleward or equatorward, according to the surface (whether land or water) over which it passes. Differences in climate along the same latitude circle necessarily result.

It has been of very great importance in the history of the United States that the continent of North America broadens to the north and narrows to the south, and does not become narrower in the middle and higher latitudes as South America does. The races which have migrated from Europe to make up the American people have thus been able to spread over a vast extent of country in the temperate zone having climatic conditions not very unlike those of their Old World homes. Were the continent broadest to the south, in the trade wind zone, an American Sahara would replace the Gulf of Mexico, and the great agricultural regions of the United States would be correspondingly less extensive. The usefulness of North America as a new home for the overflowing populations of Europe would under such conditions have been very greatly restricted. In the present distribution of the foreign-born in the United States an influence of climatic controls may be seen, although many other factors — political, social, and economic, together with transportation facilities — inevitably play a part.

The relative preponderance of land or of water influences

[1] See Chapter V.

depends upon a number of factors, such as distance from the ocean; the direction of the prevailing winds; the presence of mountains in the way of onshore winds, etc. In the United States the controlling water areas are (1) the Pacific and Atlantic oceans; (2) the Gulf of Mexico and, to a much less degree, the Great Lakes. Neither of the two oceans can attain its maximum control over the climate of the adjacent continent: the Pacific, because of the presence of the massive mountain barrier near the coast; the Atlantic, because it is on the leeward side of the continent. On the narrow Pacific coastal slope the climates are unlike those elsewhere in the country and in many respects resemble those of western and southern Europe. Being exposed to the influence of the Pacific, with the prevailing winds blowing directly from the conservative ocean, the climates are on the whole relatively mild and equable, with slight seasonal fluctuations. The seasonal contrasts are most marked where the marine influence is lessened, as in the valleys to the east of the Coast Range. The slope thus has various types of transitional littoral climates, with increasingly marked continental features over the sections which are most effectively shut off from the ocean influences.

The influence of the Atlantic Ocean is much diminished by the fact that the prevailing winds are offshore. Hence it follows that there is not very much of the tempering effect usually associated with the conservative ocean waters. The Atlantic coastal belt, except when the winds temporarily blow onshore, does not differ very much from the interior. This is clearly seen on the chart of mean annual ranges of temperature. Fairly large ranges, characteristic of a continental interior, are carried eastward to the coast, and even over the ocean for some distance offshore.[1] Thus along the Atlantic coast the summers are warm and the winters are cold. The climate is not littoral. It is continental. The Southern states naturally have milder winters than do the states along the northern Atlantic coast, owing to the lower latitudes and the greater frequency of warm winds in the South. The importance of the Atlantic Ocean as a source of water supply is, however, very considerable.

[1] See *Atlas of Meteorology*, Plate 2, text page 8.

The Gulf of Mexico is an important control of the climates east of the Rocky Mountains. It is a very warm body of water.[1] Its maximum effects are seen during the summer months, for then the prevailing winds over most of the eastern United States are from southerly directions. These winds are well laden with vapor, and it is to them that much, if not most, of the summer rainfall over this eastern area is due. Furthermore, throughout the year and especially in winter, temporary warm and damp winds associated with passing storm conditions blow with considerable frequency from southerly directions, and thus carry the warming influence of the Gulf of Mexico far northward. These warm spells temper the winters of the northern districts, interrupting the severe cold that comes with the westerly and northwesterly winds from the northern continental interior. In summer these southerly spells are hot, muggy, and depressing. The sharp contrast between the weather type which is associated with cold northerly winds and that which comes with warm southerly winds from the Gulf is one of the striking and characteristic features of the climates of much of the great region east of the Rocky Mountains.

The Great Lakes are of relatively subordinate importance as major climatic controls, but they show local effects which are in many cases of distinct economic significance.[2]

Mountain Barriers. Mountain ranges, especially when high and extended, are effective climatic barriers. If they stand in the path of the prevailing winds, they may bring about marked differences in rainfall, in temperature, in cloudiness, in humidity, on their opposite sides. When near a coast, especially a windward coast, they prevent ocean influences from extending inland.

The most important mountain barrier in the United States is that formed by the Pacific coast ranges (Cascades, Sierra Nevada, Coast). These western mountains prevent the influence of the Pacific from being carried far into the continent, and thus separate a narrow coastal belt, much of which has a

[1] The mean surface temperature in February averages between 68° and 77°, and in August between 82.5° and 84°.

[2] See Chapters V, VI, VIII, XI, XIII, XVI, and XIX.

modified marine climate, from an interior, east of the Sierra Nevada-Cascades, where the rainfall is less and the ranges of temperature are much greater. The influence of the western barrier upon the climates of the North American continent as a whole is accentuated by the fact that the mountain systems trend in a northwesterly direction in the higher latitudes, where the continent broadens, thus limiting the marine influences still further to the more immediate Pacific coast. The situation is quite different in Europe, where there are no high west coast mountains and where, for this reason and because the windward margins of the continent are much indented by numerous water bodies, the ocean influence is carried far inland by the prevailing westerly winds. The Rocky Mountains, together with their collateral ranges, are far less important as a climatic barrier than they would be were there no Pacific ranges. The latter being farther to windward naturally have the greatest effect. The influence of the Rocky Mountains is seen in their local effects upon rain and snowfall, in their acting as a barrier against the spreading of cold waves over the Plateau region from the east, in the warming which bodies of air undergo as they descend the slopes (chinook winds), in the differences which often prevail between the weather types to the east and west of the Continental Divide, and in other ways.

The Appalachians as a whole are not an effective barrier. They are not high. They are near the leeward margin of the continent. They are more or less parallel to the direction of the prevailing winds during much of the year. The amounts of rainfall on their eastern and western slopes do not, taking the system as a whole, show very marked and persistent differences. Even in winter they do not protect the districts to leeward from invasions of continental cold. The Appalachians do, however, show many local barrier effects upon the climates of their immediate surroundings. The fact that the lesser mountain barrier is on the east of the continent, and the greater barrier on the west, made it easy for the early settlers to cross the Appalachian area through the natural gateways, and then to expand over the great interior lowlands where they found favorable climatic conditions.

It is one of the striking characteristics of the topography of the United States that there is no great transverse (that is, east and west) mountain barrier. In going from south to north, or vice versa, no sudden changes in climate are met with. The gradations are slow and gradual. The climatic subdivisions are therefore separated by north-south lines rather than by east-west lines. The influence of the Gulf of Mexico would be much diminished if there were a transverse range of high mountains across the Mississippi Valley. Such a range would cut off from the districts to the north of it the warm southerly winds and the rainfall which now have free access from the Gulf. The severity of the winters would therefore be considerably increased over the northern tier of states east of the Mississippi River. A transverse mountain range, on the other hand, would be a great protection to the Southern states in winter, in keeping out the cold northwest winds, which now have a free sweep from the western plains of Canada to the Gulf and often cause great damage to crops in the Far South. These same cold northwest winds, in spite of the economic losses which they may bring, are invigorating and help to counteract the enervating effects of too steady warmth.

The fact that the western mountain barriers to a considerable extent prevent the direct importation of water vapor from the Pacific Ocean into the interior of the country adds very greatly to the importance of the control which the Gulf of Mexico can exert over the rainfall of the eastern United States. From the Gulf comes an abundant supply of rainfall which to a large extent compensates for the loss resulting from the presence of the western mountains. If there were no Gulf of Mexico, or if there were a high transverse mountain barrier across the Mississippi Valley, the rainfall over much of the United States east of the Rocky Mountains would doubtless be far less favorable for agricultural purposes and for the homes of a large population. Indeed, it is probable that semi-aridity might to a considerable extent replace the present sufficient and well-distributed rainfall over much of our best farming land.

Altitude. The barrier effects of mountains are simply due to the obstacle that mountain ranges put in the way of climatic

conditions which would otherwise be similar on the opposite sides of the barrier. A narrow wall as high as the respective mountain ranges would accomplish essentially the same results. In addition to this simple barrier effect, mountains and highlands have certain special climatic peculiarities because of their elevation above sea level. It is here that the control of climate by *altitude* is met. Mountain and plateau climates are always placed in a group by themselves as distinguished from those of lowlands. The former, as contrasted with the latter, are characterized by a general decrease in pressure, temperature, and absolute humidity; an increased intensity of insolation and radiation; larger ranges in soil temperature; higher wind velocities; usually a greater frequency of rain and snow and, up to a certain altitude, more of it. Inversions of temperature are frequent characteristics of the colder months and of the night. Such conditions often give mountains the advantage of higher temperatures than the adjacent valleys or lowlands — a fact of importance in connection with the use of certain mountain stations as winter resorts. In summer, altitude gives relief from the heat of the lowlands.

Broad generalizations such as these serve only for the purposes of a very brief summary. The local topography is of prime importance in bringing about many modifications in climatic conditions. The occurrence of frost in valleys, for example, is a well-known fact. Mountains both modify the general winds and give rise to local winds. Among the latter mountain and valley winds are often of considerable hygienic importance in their control of the diurnal period of humidity, cloudiness, and rainfall. In the United States the greatest and most widespread effects of altitude are naturally found in the western plateau and mountain region, where the varied topography gives rise to a great variety of local climates. In the east the elevations are less, and the area occupied by highlands is less extended. Nevertheless there are many local topographic effects on climate in this section also. Among these may be mentioned as illustrations the heavy rainfalls of the eastern and southern slopes of the southern Appalachians; the popularity as summer resorts of the White Mountains of New

England, the Adirondacks of New York, and many other portions of the mountain and plateau country along the Atlantic seaboard. If there had been no Appalachian highland area in the Southern states, with its plateaus and slopes unsuited to the growth of tobacco and cotton and sugar cane, these typical southern crops and the negro labor which they necessitated would doubtless have occupied much of the area which, with its more temperate plateau and mountain climates, was actually settled by a very different sort of population, engaged in different occupations.[1]

Prevailing Winds.[2] Most of the United States lies in the belt of the storm-bearing prevailing westerly winds, but the Gulf of Mexico region is far enough south to reach into the northeast trade belt. As winds are of critical importance in controlling weather types, their direction and velocity must be considered in any study of climate. The prevailing wind in summer may be a very warm one, as is the case over most of the eastern United States, where southwesterly wind directions are dominant during the hot months. Such conditions naturally increase the summer heat. Or the prevailing winter wind may be a cold one, as in New England, thus making the winters more severe. The reversal of the prevailing winds under the control of passing conditions of high or low pressure is frequent all over the United States, especially in the North and in winter.

The great permanent areas of high and of low pressure over the oceans adjacent to North America — the so-called "centers of action" — play a considerable part in determining the directions of the prevailing winds on the continent. The low pressure system over the northern North Atlantic exerts a marked control over the prevailing northwesterly winds of the northeastern United States in winter. The tropical high pressure belt of the North Atlantic has an important share in determining the great flow of southerly winds over the southern and eastern

[1] W. N. Lacy, "Some Climatic Influences in American History," *M. W. R.*, Vol. 36 (1908), pp. 169–173. (When the *Monthly Weather Review* is referred to in these footnotes the abbreviation *M. W. R.* is used.) See also idem, "Weather Influences preceding the Evacuation of Boston, Massachusetts," ibid., pp. 128–129.

[2] For a full discussion of this subject see Chapter VII.

portions of the country throughout the year, as well as in controlling the general character of the seasons in the eastern United States. On the Pacific coast a low pressure area over the northern North Pacific in winter largely controls the prevailing southwesterly and westerly winds of the northern portion of this coast, and the tropical high pressure belt lying farther south also influences the wind directions, especially along the southern portion of the coast.

Ocean Currents. Too much emphasis is usually laid on ocean currents as controls of climate. It should be remembered that an ocean current can have practically no influence on the climate of an adjacent land unless the wind is blowing onshore. Further, ocean waters themselves, without the help of any ocean currents, are conservative bodies, and therefore tend to temper the cold or the heat of any land over which their influence may be carried. It is true enough that the Gulf Stream and the Gulf Stream Drift do keep the North Atlantic waters off the eastern coast of the United States warmer than they would otherwise be, and that the Labrador Current is a cold flow which chills these same waters to a lower temperature than they would otherwise have. And on the Pacific side the Japan Current, flowing southward along the coast, with a subordinate eddy circling around the Gulf of Alaska, certainly helps to keep the Pacific slope climates rainier and more temperate than they would be without that current. A glance at the isothermal charts of the world at once shows the effects of these currents in deflecting the isotherms. Off the Pacific coast of North America the isotherms are carried equatorward by the southward-flowing cool current passing along California and Mexico, and poleward by the eddy which flows from right to left around the Gulf of Alaska. The result is a spreading apart of the isotherms and a tendency toward an equalization of the temperatures along the coast. On the Atlantic side, on the other hand, the isotherms are crowded together. The Gulf Stream carries them northward along the southern and central portions of the coast, while the Labrador Current carries them southward along the coast of New England and the Canadian provinces.

Storm Control. Climate itself being the resultant of diverse weather conditions, cyclones and anticyclones which determine the weather from day to day are essential climatic controls. Although storm control is here mentioned at the end of the list of climatic controls, it should be remembered that, as already indicated at the beginning of this chapter, the relative importance of these controls over weather and therefore over climate varies greatly. Thus, for example, if the weather of a certain section happens to be distinctly under storm control for part of the year, the influence of the other controls, such as latitude, land and water, altitude, etc., may be largely or even wholly overcome by the conditions resulting from the prevalence of cyclonic winds and clouds. In such a case, storms should be placed at or near the head of the list of controls of climate rather than at the end. This whole subject of the weather element in climate is of sufficient importance to warrant its consideration in a later chapter (Chap. IV).[1]

[1] Many of the other points briefly touched upon in Chapter II are also discussed at greater length in later sections.

CHAPTER III

CLIMATIC PROVINCES OF THE UNITED STATES

NEED OF A CLASSIFICATION OF CLIMATIC PROVINCES · VARIOUS OFFICIAL CLASSIFICATIONS · GREAT VARIETY OF SUGGESTIONS POSSIBLE · ESSENTIALS OF A WORKING SCHEME OF CLIMATIC PROVINCES · THE EASTERN PROVINCE · THE GULF PROVINCE · THE PLAINS PROVINCE · THE PLATEAU PROVINCE · THE PACIFIC PROVINCE

Need of a Classification of Climatic Provinces. In dealing with the climatology of an area as large as that of the United States it is necessary, if the discussion is to be clear and systematic, to adopt some scheme of subdivision into climatic districts or provinces. Many suggestions have already been made along this line.[1]

Various Official Classifications. The United States Signal Service and Weather Bureau have at various times adopted different subdivisions, but these have all been groupings of districts and stations for convenience of administration, of forecasting, of the collection of data, or of reference, rather than climatic provinces. Hence state or purely arbitrary lines

[1] W. L. G. Joerg has done a useful piece of work in bringing together reproductions of the most important classifications of the natural regions or provinces of North America and of the United States. Twenty-one different schemes are presented. Eight are grouped as *structural,* four as *climatic,* two as *vegetational,* one as *zoögeographic,* and six as *natural regions.* In addition, the writer gives a new classification in which he has selected what seems to him best in the others ("The Subdivision of North America into Natural Regions: A Preliminary Inquiry," *Annals Assoc. Amer. Geogr.*, Vol. 4 (1914), pp. 55–83. Also gives references to other classifications not especially considered in the article. It adds greatly to the convenience of the reader that one scale of map is used for all the North American classifications and one scale for all those dealing with the United States). See also R. DeC. Ward, "The Classification of Climates," *Bull. Amer. Geogr. Soc.*, Vol. 38 (1906), pp. 401–412, 465–477; "Climate considered especially in Relation to Man" (2d ed.), 1918, chap. iii; and "A New Classification of Climates," *Geogr. Rev.*, Vol. 8 (1919), pp. 188–191. For the western portion of the United States see W. G. Reed, "Climatic Provinces of the Western United States," *Bull. Amer. Geogr. Soc.*, Vol. 47 (1915), pp. 1–19.

have generally been taken as the limits of the different divisions, although the larger topographic features, such as the Rocky Mountains and the Sierra Nevada-Cascades, have also been used.[1]

For the general purposes of the publication of climatic data the Weather Bureau has adopted one hundred and six Climatological Sections, determined partly by state lines and partly

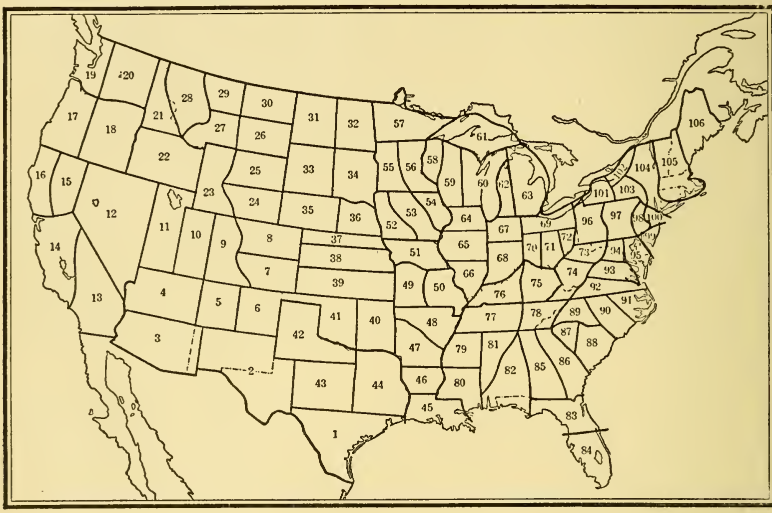

FIG. 2. Climatological Sections adopted by United States Weather Bureau

by considerations of administrative convenience. When the longer axis of a state runs in a north-south direction, the state is usually divided latitudinally so as to show the differences between the northern and southern portions. In cases where states are crossed by a main drainage system, they are so divided as to keep the drainage area wholly within one subdivision or section (Fig. 2). This scheme is adopted in the *Summary of the Climatological Data of the United States by Sections.*

[1] See H. H. C. Dunwoody, "Weather Proverbs," *U. S. Signal Service Notes,* No. IX (1883); F. Waldo, "Elementary Meteorology" (1896), p. 318; "Forecast Districts of the United States," *M. W. R.*, Vol. 44 (1916), p. 587.

Great Variety of Suggestions Possible. The great variety of suggested subdivisions, whether primarily physiographic, botanical, zoölogical, climatic, or natural regions, is confusing. Moreover, there is no limit to the number of possible classifications, for these depend on any author's special interest or view point, which may be climatic, botanical, physiographic, or one of administrative convenience. Even on the basis of climate alone an almost infinite number of classifications might be proposed, for the criterion adopted may be certain special conditions or values of one climatic element, or various combinations of two or more elements.

Essentials of a Working Scheme of Climatic Provinces. In devising a scheme of climatic subdivisions there are a few essential considerations which should be kept in view. The classification must be simple. The separate divisions should, when possible, be bounded by large and easily recognized physical or political lines. Arbitrary limits, difficult to remember and to locate, should be avoided if possible. The scheme ought not to be too individual, and should commend itself to those who wish to use it on the ground of its being rational and practical. In any climate in which the cyclonic and anticyclonic control of weather types is a distinguishing characteristic the climatic subdivisions should be determined with due regard to this control.[1] In other words, the subdivisions should be chosen because of their special relations to cyclonic and anticyclonic tracks and movements, to local and characteristic weather distribution around lows and highs, to cyclonic and anticyclonic winds, and because of the general similarity of weather types over each province. Finally, the districts should, as far as possible, be the same as those which have been officially adopted in the publication of the meteorological and climatic data of the region. If, for example, the published data are grouped according to one scheme while the climatic subdivisions are based upon a different scheme, there is great inconvenience in the use of these data.[2] To take the specific case

[1] See Chapter IV.

[2] In A. J. Henry's "Climatology of the United States," *U. S. Weather Bur. Bull. Q*, 1906, the numerical data are all given by states.

of the United States. When there is no good and sufficient reason for using other boundaries, state lines and the divisions adopted in the Weather Bureau's Climatological Sections are both convenient and practical. Such a classification of climatic provinces makes it an easy matter to look up the special and detailed characteristics of each subdivision in the official publications of the Weather Bureau.

In the United States there are three great natural topographic and climatic subdivisions. These are (1) the eastern, embracing about half of the whole area, from east of the Rocky Mountains to the Atlantic Ocean and the Gulf of Mexico; (2) the western mountain and plateau district; (3) the narrow Pacific slope. Nowhere in the United States are sudden changes in climate to be met with in going from north to south, or vice versa. The transition is everywhere slow and gradual. The natural climatic subdivisions are therefore separated by north-south lines and not by latitudinal lines. So far as east-west boundaries are necessary, these are therefore inevitably largely arbitrary.

The Eastern Province. The Eastern climatic district has a remarkable uniformity in its weather types and in its climate. It is freely open to east, north, and south; to the Atlantic, to Canada, and to the Gulf of Mexico. Its seasons are strongly contrasted. Its winter temperature gradients between north and south are unusually steep. Its continental climate reaches to the Atlantic seacoast, with little modifying effect of the ocean waters. Its rainfall is, as a whole, plentiful and well distributed throughout the year. Its frequent and well-developed cyclones give it many rapid and marked weather changes and sharply contrasted weather types, controlled to a large extent by the diversity of temperature and of moisture conditions of the district from which the winds come. With the approach toward the Rocky Mountain area on the west there comes also a gradual transition to the drier, sunnier, and less cyclonically controlled climate of the Great Plains and the eastern foothills. There is here no easily fixed and sharply determinable climatic boundary, although the lines of equal rainfall, cloudiness, and relative humidity all trend very generally north and south.

The 100th meridian, the critical mean annual isohyetal line of 20 inches, and the 2000-foot contour line are all reasonably satisfactory. For the present purpose the generalized line which follows the 2000-foot contour has been selected. This agrees fairly well with the 20-inch isohyetal line, and also with the 100th meridian, and marks approximately the eastern margin of the physiographic unit of the Great Plains (Fig. 3).

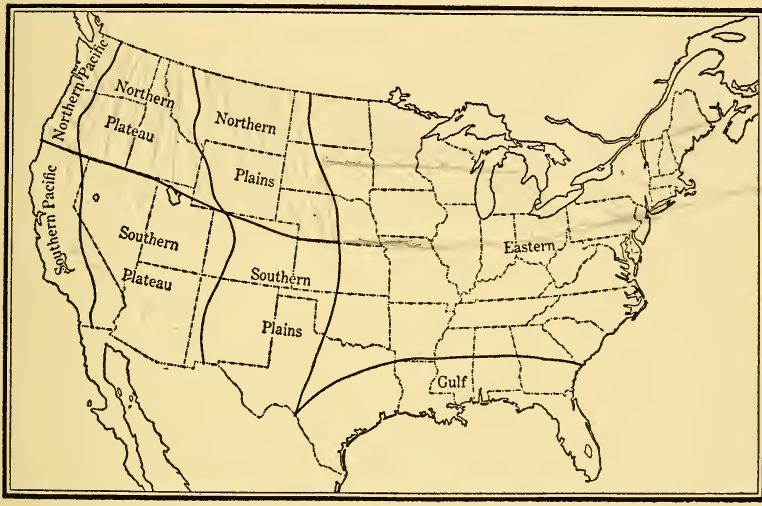

FIG. 3. Climatic Provinces

The Gulf Province. To the south, over the states bordering on the Gulf of Mexico, the temperatures are higher; the winters are much milder; the cyclonic control is weaker; the temperature and weather changes are fewer and less emphatic; diurnal phenomena are more marked; conditions are more "settled"; the rainfall is heavier and usually has a marked summer maximum. For these and other reasons the southern portion of the Eastern district may well be set apart as a subordinate climatic province. There is, however, no sharp climatic boundary of any kind which may be taken as the limit of this southern Gulf Province. Hence an arbitrary line has been drawn which includes on the south most of the Gulf coastal plain, is not far

from the position of the mean annual isotherm of 65°, marks in its central portion the northernmost position of the 100-foot contour line, and also accords with the dividing lines between four of the Weather Bureau's official Climatological Sections.

The Plains Province. The Plains climatic province in the proposed classification is included between the generalized line following the 2000-foot contour and the generalized line of the main Rocky Mountain divide. The latter may be taken as a fairly satisfactory climatic boundary in relation to rainfall, cold waves, the direction and characteristics of the winds, and the prevailing weather types. The cyclonic control is less marked over the Plains than over the Eastern Province, both because of the difference in relation to the storm tracks and because of the generally less emphatic development of the storms themselves. The climatic differences due to latitude and relation to cyclonic control are so considerable between the northern and southern Plains that a dividing line (which, however, marks no climatic boundary) may be drawn following in a general way the state lines between Wyoming, Nebraska, Colorado, and Kansas, and thus conveniently agreeing with divisions adopted by the Weather Bureau.

The Plateau Province. The Rocky Mountain divide on the east and the Sierra Nevada-Cascade divide on the west (both broadly generalized) are natural and convenient boundaries for the Plateau Province. A great interior region of mountain ranges, high plateaus, and deserts, its chief characteristic is its small rainfall. It has the minimum cloudiness and the minimum relative humidity in the United States. Comparatively few cyclonic storms cross it. A persistence of winter high pressure conditions and of summer low pressure conditions characterizes it. The rain-shadow effect of its western mountain barrier necessitates irrigation undertakings, and where these are impracticable the aridity of the desert reigns supreme. Severe cold waves of the eastern type are barred out by the Rocky Mountain barrier. Diurnal rather than cyclonic phenomena prevail, but cyclonic controls over weather are perhaps more important than is commonly believed. Mountain climates, with their special peculiarities of strong sunshine, dry

air, and large temperature ranges, are here found. An east-west line, roughly coinciding with the state boundaries of Oregon and Idaho on the north and of Nevada, Utah, and Colorado on the south, agrees in a general way with the southern boundary of the Columbia Plateau and also with boundaries of the Weather Bureau's Climatological Sections. Hence such a line may serve as a convenient division between the northern and southern Plateau Provinces.

The Pacific Province. The narrow coastal strip west of the Sierra Nevada-Cascades is the Pacific Province, with its great variety of climates, from rainy to arid, from those of the lowlands to those of the snow-covered mountain tops, from the cool summers of the coast to the great heat of the interior; with its prevailing mildness and equability, its sub-tropical rainy season and sub-tropical cyclonic controls, its great forests and its fertile agricultural valleys, its irrigated fruit orchards and its far-famed California health resorts. Between the rainier, cloudier, damper, and more changeable north and the drier and more settled south, the state line between California and Oregon is an easily determined and fairly satisfactory boundary. It does not differ greatly from the topographic divide between the states and accords with the established scheme of subdivision adopted in the publication of the Weather Bureau climatic data.[1]

[1] The climatic characteristics of the several provinces are more fully discussed in Chapter XX.

CHAPTER IV

THE WEATHER ELEMENT IN UNITED STATES CLIMATES

GENERAL RELATIONS OF WEATHER AND CLIMATE · WINTER STORM CONTROL · SUMMER DIURNAL CONTROL · COMBINED CYCLONIC AND DIURNAL CONTROL OF SPRING AND AUTUMN · SEASONAL GROUPING OF CYCLONIC PATHS · WINTER CYCLONIC PATHS · SEASONAL VARIATIONS OF STORM PATHS AND OF WEATHER TYPES · PATHS OF ANTICYCLONES IN THE UNITED STATES · SUMMER CYCLONIC PATHS · SPRING AND AUTUMN CYCLONIC PATHS · THE IDEAL CYCLONE AS COMPARED WITH THE ACTUAL CYCLONE · CYCLONIC WEATHER CONTROLS IN DIFFERENT SECTIONS · WINTER WEATHER TYPES OF THE EASTERN CLIMATIC PROVINCE · SUMMER WEATHER TYPES OF THE EASTERN CLIMATIC PROVINCE · SPRING WEATHER TYPES OF THE EASTERN CLIMATIC PROVINCE · AUTUMN WEATHER TYPES OF THE EASTERN CLIMATIC PROVINCE · CURVES ILLUSTRATING WEATHER TYPES OF THE NORTHEASTERN UNITED STATES · EACH SECTION HAS ITS OWN WEATHER TYPES · WINTER WEATHER TYPES OF THE PACIFIC PROVINCE · SUMMER WEATHER TYPES OF THE PACIFIC PROVINCE · WINTER WEATHER TYPES OF THE PLATEAU PROVINCE · SUMMER WEATHER TYPES OF THE PLATEAU PROVINCE · WINTER AND SUMMER WEATHER TYPES OF THE PLAINS PROVINCE

General Relations of Weather and Climate. Careful records of *weather*, continued for many years, give *climatic averages.*[1] In the temperate zones the weather is largely controlled by a succession of cyclones and anticyclones, more or less irregular in their occurrence, uncertain in their progression and duration, and differing considerably in their characteristics. Hence weather changes are correspondingly irregular, uncertain, and diverse. The nature of these changes depends on the degree of development, the velocity of progression, the track, and other conditions of the disturbance which produces them. Of weather types there is an almost endless variety. Their detailed study belongs under meteorology. Yet these types give climates their distinctive characters, to a large extent deter-

[1] See Julius Hann, "Handbuch der Klimatologie," Vol. 1 (2d ed.), 1897. Translated by R. DeC. Ward, 1903.

mining the amount and the distribution of temperature, of precipitation, of humidity, and of cloudiness. A general understanding of the nature of the cyclonic and anticyclonic control is therefore essential to a proper appreciation of climate. Anyone who seriously attempts to study the climatology of the United States should have a series of weather maps in one hand and a set of climatic charts of the country in the other. He will very soon realize that the better his understanding of the former, the more intelligent is his appreciation of the latter.

The essence of this cyclonic control is its irregularity. It is obvious, therefore, that its effects upon all the meteorological elements must largely disappear when the conventional time units are taken as the basis for averaging climatic data. Annual, monthly, and diurnal averages of the different climatic elements, when given numerically or even when charted, are therefore often misleading. They give but a lifeless picture. They do not show how and why the conditions which they aim to represent were really brought about. It is the irregular weather changes from day to day which give climates their real character, affecting man's activities, his crops, his comfort, and his health.[1] The *average* or *normal* weather of a season, a month, or even a day, is known for much of the country. But average weather is not what may actually happen. And it is the actual, not the normal, which is really experienced.

We should therefore try to picture to ourselves the series of weather types which, varying seasonally and regionally, make up the average sum-total of what we call climate. The more pronounced types have a certain well-marked individuality and a more or less systematic recurrence. As they depend so largely upon the passage of cyclones and anticyclones, the movements of these areas across the United States must first be considered. This will lead to an understanding of the more marked weather changes associated with their passage.

[1] For a fuller discussion of this subject see R. DeC. Ward, "Suggestions concerning a more Rational Treatment of Climatology," *Report VIII Int. Geogr. Cong.*, Washington, D. C. (1905), pp. 277–293 (contains numerous references); W. G. Reed, Jr., "The Study of Phenomenal Climatology," *Quart. Journ. Roy. Met. Soc.*, Vol. 36 (1910), pp. 39–48; A. J. Henry, "February Weather," *M. W. R.*, Vol. 42 (1914), pp. 107–111.

Most of the United States is well within the belt of prevailing westerly winds, one of whose most marked characteristics is the continuous procession of cyclonic and anticyclonic disturbances which keeps marching eastward in a great spiral circuit around the north pole. Over the temperate zones as a whole there is thus a great ring of stormy weather, oscillating poleward and equatorward as the sun moves to and fro in the course of its regular migration. Northward across the United States swings this storm belt as the summer sun comes north of the equator. Southward it swings in winter, following the declining sun, covering the country even to the Gulf of Mexico. Scattered through the southern quadrants of the larger cyclonic storms, especially during the warmer months, come more local disturbances — thunderstorms and tornadoes. There is thus a second belt of local storms, south of the general cyclonic storm belt. This also swings back and forth seasonally, covering practically the whole country in summer and being carried well into and even across the Southern states in winter.

Winter Storm Control. Weather types vary seasonally and geographically. These types result from a combination, more or less irregular, of periodic, diurnal elements, under the control of the sun, and of non-periodic, cyclonic and anticyclonic elements. In winter, when practically the whole country is under the influence of the storm belt and when the sun is low and the days are short, the non-periodic control is everywhere strongest. Local conditions of heat and cold largely become subordinate to the general control by the cyclone and anticyclone, which import winds and weather from a distance. The irregular changes from clear to cloudy, from warmer to colder, from dry air to snow or rain, extend over large areas and show but little diurnal control. Storms are not only more widely distributed over the country in winter, but are then larger, more frequent, more violent, and move faster. Hence changes of wind, temperature, and weather occur oftener, are more sudden, and more emphatic during that time. The Northern states, and especially the Northeastern states, being most frequented by winter storms, have the most changeable weather, the alternation between fair and stormy being repeated with consider-

able regularity and frequency. This cycle of cyclonic changes is run through in about two to four days. With increasing distances to the south and west, the general storm control weakens; less cloudy and stormy weather occurs, and the temperature changes are less sudden and less marked. Thus it is that the Southern states and especially the Southwestern states have on the whole more settled, "better" winter weather and more uniform temperature conditions than the Northern states. New Mexico, Arizona, western Texas, southern California, for example, are so far removed from the most frequented storm belts, and their own cyclones are on the whole so weak, that they enjoy an abundance of sunshine and have little precipitation, and that mostly in brief showers. The Gulf states, and especially Texas, are, however, exposed to occasional invasions of severe cold from the north, when winter cyclones, traveling well to the south, are followed by cold waves.

Summer Diurnal Control. From the irregular storm control which is so powerful in winter to the dominant solar control of summer is a characteristic change which, year after year, is accomplished with the orderly sequence of the seasons. In summer, when the general storm belt swings to the north, followed on its southern side by the thundershower belt, the cyclonic element in weather changes is weakest. The cyclone, with its irregular control over all weather elements, gives way to the sun. In place of the turbulent atmospheric circulation of the colder months come the gentler movements of the warmer months. The temperature distribution the country over is remarkably uniform. The prevailing temperatures are high, the variations small, the gradients weak. The dominant weather types are associated with the regular changes from day to night. Periodic, diurnal phenomena replace non-periodic, cyclonic phenomena. Cumulus clouds, especially noticeable on days which follow rainfalls; diurnal variations in temperature and in wind velocity; afternoon thunderstorms, recurring in spells with considerable regularity, characterize the warmer months over most of the country and present an analogy with tropical conditions. Cyclonic and anticyclonic spells of hotter or cooler weather, rainy or dry weather, with varying winds

differing in the temperatures and moistures which they bring, serve to break the regularity of the simple, diurnal, sun-controlled types. Summer is the season of weak, poorly developed, slow-moving storms, mostly following the northern border; of few nimbus clouds; of local rather than widespread general rains; of relatively small changes of temperature; of light and variable winds. The squall winds of passing thunderstorms and the violent inrushing blasts of tornadoes are local and temporary interruptions of the generally calm and peaceful régime of summer weather. The Southern and Western states, being well removed from the storm belt, have a succession of typical "settled" diurnal changes, day after day, with few general rains, but share with most of the country the local disturbances characteristic of the thunderstorm belt. The northern tier of states, east of the Rocky Mountains, being at the southern margin of the summer storm belt, experiences the irregular changes which result from the eastward progression of summer cyclones. These changes are, however, far less marked than in winter. They are often little more than a series of warmer and cooler spells, often repeated fairly systematically in a period of roughly about four to eight days, with thunderstorms and long periods of uniform temperatures interspersed.

Combined Cyclonic and Diurnal Control of Spring and Autumn. Spring and autumn are transition seasons and have their own transitional weather types. In spring the growing diurnal element is marked by the increasing importance of local controls; by the appearance of convectional phenomena such as cumulus clouds and April showers; by the struggle between cyclonic and solar controls of temperature, now one being paramount and now the other, but the latter gaining and the former losing. The storm control becomes increasingly uncertain and weaker; the storm movements are slower and more erratic. Irregularly, spasmodically, is the transition from winter to summer accomplished. Wintry spells are interpolated between summer spells. But the latter become more marked, last longer, and advance farther northward, as the former come less frequently, are less emphatic, and gradually withdraw to higher latitudes. March is usually a turbulent and unpleasant month in northeastern

sections, with quick alternations of wintry conditions and of types indicative of approaching summer.[1]

With the passing of summer into autumn the sun's rays become more and more oblique, and weaken; the temperature falls; the days grow shorter; the control of the weather passes gradually but irregularly from the sun back again to the cyclone, from the mildness of summer to the turbulence of winter. The decrease in diurnal phenomena such as local thunderstorms is an autumnal characteristic. As autumn draws to its close, the irregular cyclonic régime of winter is once more established. It is in the north and east, close to the most frequented storm belts, that the cyclonic control continues longest in spring. So it is also in these same districts that the storm control makes itself felt early in autumn.

Seasonal Grouping of Cyclonic Paths. It is a mistake to picture to ourselves any rigid system of clearly defined storm "tracks." There are, rather, certain broad belts or districts over which cyclones travel more frequently than elsewhere. For the present climatological purpose it is best to generalize very broadly, showing these most frequented regions as wide belts, and realizing that there is no very close and definite relation of cyclones to these paths. For the sake of simplicity the year may be divided into three parts. Each of these divisions has its own more or less distinctive meteorological characteristics, cyclonic and anticyclonic belts, and weather types. December, January, February, and March are here taken as winter months; June, July, August, and September are summer months; April and May, October and November, are spring and autumn months respectively.[2]

[1] O. L. Fassig has shown that the types of weather, storm paths, and amount and character of precipitation in March depend upon the relations and development of the continental, the Atlantic, and the Pacific anticyclones ("Types of March Weather in the United States," *Amer. Journ. Sci.*, 4th Ser., Vol. 8 (1899), pp. 319–340). On the variability of March weather see A. J. Henry, "Climatology of the United States," *U. S. Weather Bur. Bull. Q* (1906), pp. 81–84.

[2] The outstanding and also the most recent official publications are the following: E. H. Bowie and R. H. Weightman, "Types of Storms of the United States and their Average Movements," *M. W. R. Suppl. No. 1*, 1914; "Types of Anticyclones in the United States and their Average Movements," ibid., *Suppl. No. 4*, 1917. See also F. H. Bigelow, "Storms, Storm Tracks, and Weather Forecasting," *U. S. Weather Bur. Bull. No. 20*, 1897; A. J. Henry, "Climatology of the

Winter Cyclonic Paths. Most winter cyclones appear first on the weather maps of the United States in the region north of Montana (Alberta, or Northwestern, type), and are offshoots from the great cyclone over the North Pacific Ocean (Fig. 4). Thence they travel southeast and east along a path which is known as the northern circuit, across the Great Lakes, and down the St. Lawrence valley to the Atlantic Ocean. The time

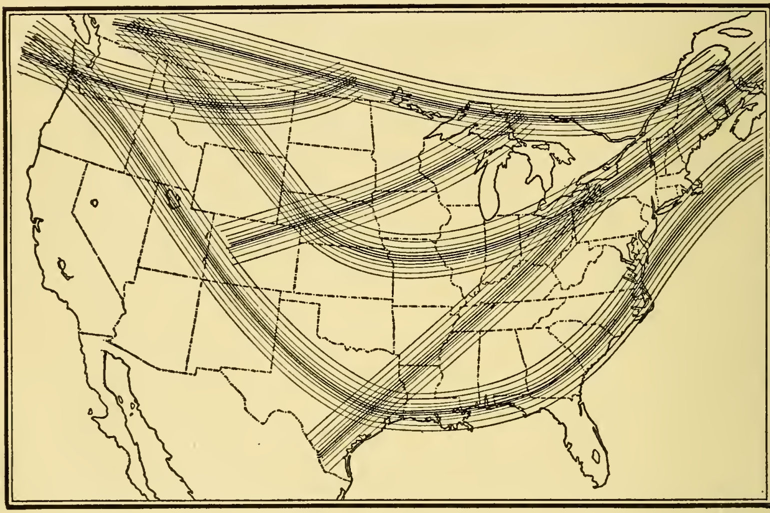

FIG. 4. Generalized Winter Storm Paths

usually occupied for this journey is between three and four days.[1] Some of these storms, especially in the colder months, loop southward down the eastern Rocky Mountain slope even as far as the western Gulf, and then move northeast. When a

United States," ibid., *Bull. Q*, 1906; idem, in "Weather Forecasting in the United States," by a Board composed of A. J. Henry, E. H. Bowie, H. J. Cox, and H. C. Frankenfield, *U. S. Weather Bur. No. 583* (1916), pp. 93–141; H. J. Cox, "Influence of the Great Lakes upon Movement of High and Low Pressure Areas," *Proc. 2d Pan-Amer. Sci. Congr., Washington, U. S. A., December 27, 1915, to January 8, 1916,* Sect. II: Astronomy, Meteorology, and Seismology, Vol. II (1917), pp. 432–459. The general description of storm types here given is based on these official discussions. Fig. 5, below, is that given by Bigelow, loc. cit.

[1] To eastern Dakota one day, to Lake Superior two days, and to middle St. Lawrence valley three days.

new storm comes in from the northwest there is frequently an anticyclone over the Southern or central states, moving east slowly, and a retreating cyclone in the northeast.

From the northern Pacific coast comes a considerable procession of storms (North Pacific type) which move eastward on the northern circuit and are probably secondaries from the Aleutian low. Some of this group, especially in winter, make a wide swing southeastward to the southern Plains, at times even reaching the Gulf coast, and then travel east or northeast. This southern storm belt is known as the southern circuit. For the transcontinental journey from the Pacific to the Atlantic about four days are needed, this being, it will be observed, a little more rapid than the rate of travel of a through express train making the same trip. Other storms of this type first make a loop to the southeastward over the Plateau region and then move northeast to the Lakes. Another group of storms, of considerably less importance, comes from the southern Pacific coast (South Pacific type), and is characteristic of winter. These usually travel rapidly to the east and northeast, but occasionally they are delayed and may last for several days over the Far Southwest. This group of South Pacific storms is not shown in Fig. 4.

From in or near Colorado (Colorado type) comes a group of storms which usually joins the northern circuit in the lake region, or may travel eastward on the southern circuit.[1]

From Texas and the Gulf of Mexico another group moves northeastward across the central valleys to the lower Lakes and thence eastward down the St. Lawrence valley; or, taking the outside track east of the Appalachians, it travels along the Atlantic coast to the Maritime Provinces. The journey to New England is accomplished in about two days, but an anticyclone over the Gulf of St. Lawrence may delay the progress of the storm a day or two. As pointed out by Bigelow, the Texas (Texas, or Southwestern, type) storms have much in common with the Colorado type just noted, but the whole pressure system of the former is about a day's journey farther along.

[1] One day to Illinois, two days to northern New York, and three days to the Gulf of St. Lawrence.

Other storms from the Gulf of Mexico (East Gulf type) start even farther east on the southern circuit than the Texas type, and some storms appear on the southern Atlantic coast and move northeast (South Atlantic, or Coast, type). Additional storm types are recognized by the Weather Bureau as Northern Rocky Mountain type and as Central type. The former are more or less like the Alberta, or Northwestern, group, but are few in number; the latter, also relatively unimportant, are chiefly secondaries.

The larger facts of winter storm movements stand out clearly: the two main circuits, northern and southern; the spur tracks leading from one to the other; the marked southward looping; the convergence of all the storm paths toward the northeast. This northeastern section must obviously have very changeable weather.

Seasonal Variations of Storm Paths and of Weather Types. These storm paths themselves and the number of storms which follow given paths are not fixed. They vary somewhat from year to year, and probably also in longer periods. Such variations control the character of seasonal weather types. The types normally characteristic of the season may thus be more or less completely reversed or interrupted. If we depend solely upon the usual monthly averages of temperature and rainfall, these seasonal variations in weather types are often obscured. It is only by reference to the daily weather maps that the actual conditions can be understood. If more winter storms follow the southern circuit, there is likely to be unusually cold weather east of the Rocky Mountains; if more winter storms follow the northern paths, there are likely to be more southerly winds, higher temperatures, and fewer and briefer interruptions by cold northwesterly winds over the Southern states. The controls of such seasonal variations in storms and storm tracks are to be sought in the development and location of the larger, so-called permanent areas of high and low pressure over the continent and over the adjacent oceans.[1]

[1] See, for example, E. B. Garriott, "Long-Range Weather Forecasts," in *U. S. Weather Bur. Bull. No. 35* (1904), pp. 60–62; W. J. Humphreys, "Why Some Winters are Warm and Others are Cold in the Eastern United States," *M. W. R.*,

Paths of Anticyclones in the United States. The movements of anticyclones are closely associated with the movements of cyclones, and the quality of the weather largely depends upon the particular combinations—in position, development, and character—of these high pressure areas and low pressure areas. The main anticyclonic paths are roughly parallel to one another and are strikingly similar to those of the cyclones, the general tendency of the former being to run more southerly.

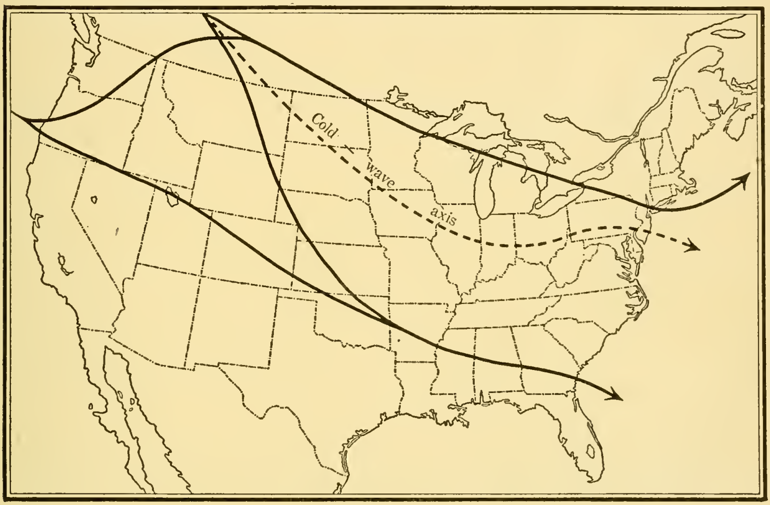

FIG. 5. Generalized Anticyclonic Paths

There are two main places of origin for anticyclones and two main paths, as shown in Fig. 5. They come either (1) from the northwest, outside the United States, in western Canada, west of the 100th meridian, or (2) from the Pacific Ocean. The latter are probably offshoots from the permanent high pressure area of the North Pacific. The first group move (1) somewhat southerly and then easterly along the northern boundary, crossing the lake region to the Atlantic coast or the Gulf of St. Lawrence, or (2) southeast from their place of origin, along

Vol. 42 (1914), pp. 672–675; E. H. Bowie, "Long-Range Weather Forecasts," in "Weather Forecasting in the United States," *U. S. Weather Bur. No. 583* (1916), pp. 341–348.

the Rocky Mountain slope to the Gulf states, thence east to the southern Atlantic coast near Florida, perhaps continuing northeast to the Gulf of St. Lawrence. These western Canadian highs are at their maximum in winter.

The second group, from the Pacific coast, also generally follow one of two broad paths. They travel either (1) northeast along the Pacific slope to Washington and Oregon and then along the northern circuit to the Atlantic coast, or (2) southeast from California to the southern Atlantic coast, crossing the mountains near Great Salt Lake. Anticyclones of this second group are limited to the warmer months, between April and September. From the northern to the southern circuit there are spur tracks, as along the eastern Rocky Mountain slope and across the northern Plateau. Some of the relations of these anticyclonic paths to weather types in different parts of the country will be considered later. In general, the winter anticyclones are well marked, and, although stationary for long periods over the Plateau region, as a whole show fairly well-defined movements along the usual paths. In summer, on the other hand, the high pressure areas are generally much less emphatic and have a much greater tendency to wander about, apparently aimlessly.

Summer Cyclonic Paths. A comparison of Fig. 6, showing the generalized summer storm paths, with Fig. 4, showing the winter storm paths, will serve to emphasize the striking difference between these two seasons in the matter of cyclonic control of weather. In summer the prevailing weather conditions are best described as "flat" and "stagnant." The cyclones — generally mild and gentle in character and not bringing widespread rains — travel on the northern circuit, with feeders from the middle-eastern slope of the Rocky Mountains and an occasional Atlantic coast storm or a West Indian hurricane. Storms rarely come directly from the northern Pacific coast. There is much less southward looping than in winter. So weak and poorly developed are many summer cyclones that after wandering about indefinitely for a time they often fade away before reaching the Gulf of St. Lawrence. The highs, also, are weaker and less emphatic than in winter.

A comparatively rare but important type of late summer storms includes the West Indian hurricanes. These, moving in from the east or northeast about latitude 25° N., recurve toward the north and usually follow the Atlantic coast to Nova Scotia. Sometimes, as in the case of the Galveston storm of September, 1900, they cross the Gulf of Mexico to the west and then travel northward across the central valleys.

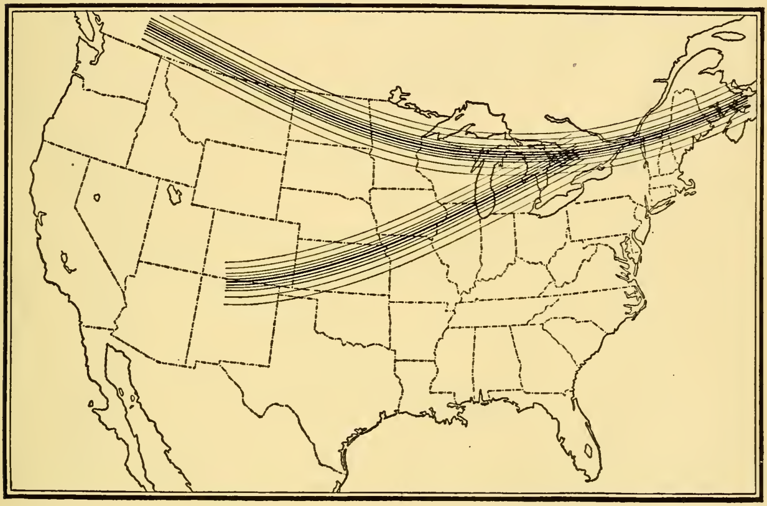

FIG. 6. Generalized Summer Storm Paths

The usual path of these hurricanes is shown in Fig. 7. The West Indian hurricanes are not regular or marked weather controllers either in summer or in autumn.

Spring and Autumn Cyclonic Paths. The storm paths for spring and autumn may conveniently be generalized together (Fig. 7). In both seasons cyclones are more or less erratic, but their southward looping is seen to be less marked than in winter and more marked than in summer. The velocity of travel in these transition seasons is less than in winter. Thus, at the end of April, storms of the Alberta type, on the northern circuit, take about one extra day for their eastward journey. In April the North Pacific type storms, when deflected far to the south,

make their journey to the Gulf of St. Lawrence in about five days. This is also the time taken by those of the Colorado type. Those from Texas also take an extra day (three days) to reach the Gulf of St. Lawrence. In spring a number of storms which are important for the eastern United States come from the middle-eastern Rocky Mountain slope and move northeast across the lake region and New England. One of

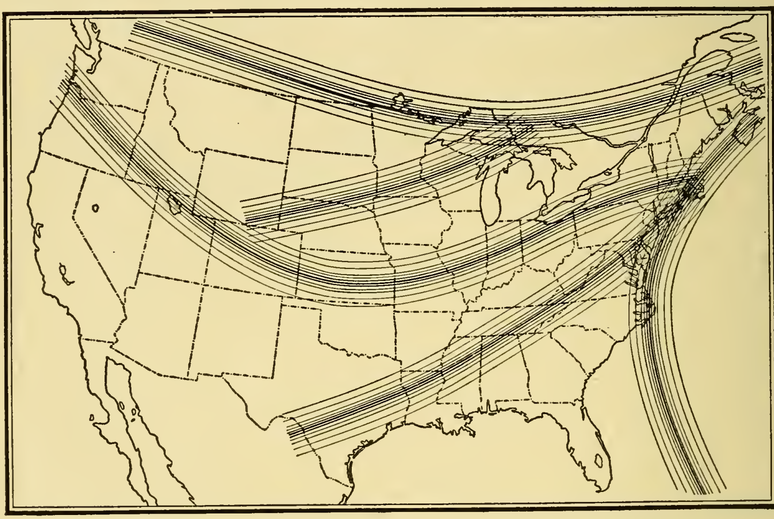

FIG. 7. Generalized Spring and Autumn Storm Paths

the characteristics of autumn is the increase in the number of anticyclones from the region north of Montana and from still farther west, and the occasional passage of a tropical cyclone along the Atlantic coast, referred to in the previous paragraph.

The Ideal Cyclone as compared with the Actual Cyclone. A diagram of the average distribution of the weather elements around an ordinary cyclone, such as is printed in many meteorological textbooks, is misleading. The impression made thereby is that cyclones are always like the ideal cyclone shown in the figure. It seems as if, when a cyclone moves across country, we should imagine this ideal diagram, presumably representing the actual weather conditions in that cyclone, to be drawn eastward across a map of the United States as if it were hung on a wire and

pulled by a string. This is a very misleading conception. Cyclones differ greatly from one another. Each has its own peculiar characteristics, although they all conform to the same general laws. They differ in character with the seasons, with the topography and general physical conditions of the region over which they move, and with the varying conditions of accompanying and preceding cyclones and anticyclones. Therefore, if an accurate and vivid impression of the weather conditions which make up and control our climates is to be secured, the weather types as they vary with the season and with the district must first be considered.

In making such a study it naturally suggests itself that one "typical" cyclone or anticyclone be followed across country, and its control over the weather in the successive sections which it passes on its eastward march be noted. This is not practicable. For it is difficult if not impossible to find cases of "typical" cyclones, following "typical" paths with average velocities and controlling the regional weather conditions in a "typical" way all across the United States. Individual type weather maps are far less satisfactory for the purpose of such an investigation than broadly generalized composite types of conditions of the same general character. The exact weather distribution of an individual map, or of a series of individual maps, will never occur again. Moreover, maps which seem to be identical do not necessarily produce identical results. Hence in the illustrations of regional weather types which follow (Figs. 8–19) no attempt has been made to reproduce any actual weather maps, or even any composites compiled by tracing from any number of selected maps. The effort has rather been to show the general conditions of pressure, temperature, winds, and weather commonly associated with cyclones of different types and over various sections of the country. These charts have been compiled after a study of some hundreds of weather maps, and are highly generalized composites, drawn free-hand.[1] It is impossible within the limits of this discussion to attempt the illustration of any considerable number of weather types. The composites

[1] The lighter shading indicates cloud; the heavier shading indicates areas of precipitation.

here given concern a few of the more common cyclonic conditions, chiefly in the eastern United States and in winter.

Cyclonic Weather Controls in Different Sections. In general it is naturally to be expected that when a cyclone is central in the Plateau Province, for example, or on the eastern Rocky Mountain slope, or in New Mexico, the amount and distribution of its precipitation will be different from that when the same storm, or a similar one, is located east of the Rocky Mountains or over the central valleys. In the first case the inclosing mountain ranges to a large extent shut out the influence of the surrounding water bodies, and may readily be supposed to interfere with the systematic development of the cyclonic wind system. The inflowing winds in the southeast quadrant may be dry and non-rainy or perhaps give only local showers. In the second case, coming as they do from the Gulf of Mexico, the winds in the southerly quadrant may cause widespread general rains. Again, when a cyclone approaches the Atlantic coast a still further difference may be observed. Then the winds throughout the eastern quadrants may be coming across water surfaces (the Great Lakes, the Atlantic Ocean, the Gulf of Mexico); there is a greater supply of moisture, and the rainfall area may be to the north of the center as well as to the south of it. Thus there is a natural difference as regards precipitation between cyclones in the western interior and in the eastern United States. In the latter the heavy rainfalls are usually found southeast of the storm center and at a distance of three hundred miles or so from it. In the eastern United States, from the Mississippi and Missouri valleys to the Atlantic coast, rain usually begins during the colder months with a falling barometer. In the warmer season, however, except in connection with general storms, the precipitation, in showers and thunderstorms, usually comes with the turn from falling pressure to rising pressure. On the Pacific coast rain generally commences with falling pressure; but during most of the time over the Plains and in the Rocky Mountain and Plateau districts rain does not begin until the cyclonic center has passed by to the south or east and the pressure is beginning to rise.

As regards their controls over temperatures, also, low pressure areas and high pressure areas differ in different parts of the country. In the east the differences between the temperatures in front of a well-marked cyclone and those in the rear, in front of the advancing anticyclone, may be 50° or 60° or more in winter. Elsewhere, as on the Pacific coast or in the south, for example, where the physical conditions are different

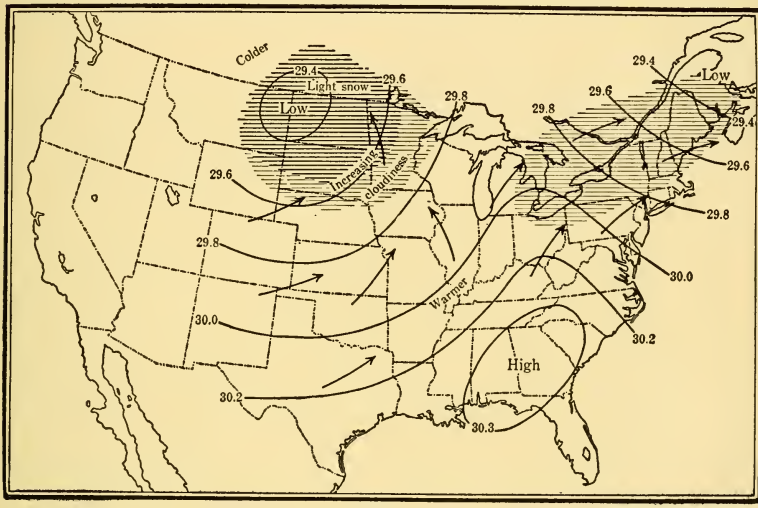

FIG. 8. Winter Storm over the Northern Plains

and where the cyclones and anticyclones may be less emphatic or differently associated, the temperature controls are very much less marked.

When winter storms of the Northwestern (Alberta) type first appear on the weather map they usually bring little precipitation, and that mostly in the form of snow in their northern and northwestern quadrants, over the northern Rocky Mountain region. The temperature is then rising, as a rule, west of the Mississippi River with southerly winds, but falling in the northwest with northerly winds, and the cloudiness is increasing over the northern Plains (Fig. 8). In twenty-four hours, more or less, the storm, meanwhile increasing in intensity, is likely to

be over the upper Lakes, attended by more precipitation (which may be in the form of heavy snows) and often by severe southerly or southwesterly gales. Over the central valleys and to the eastward the temperatures rise perhaps 20° to 30°, and with the warmer weather come clouds and rain at the southern stations and probably snow at the northern stations. Colder, clearing weather—perhaps a well-defined cold wave—follows

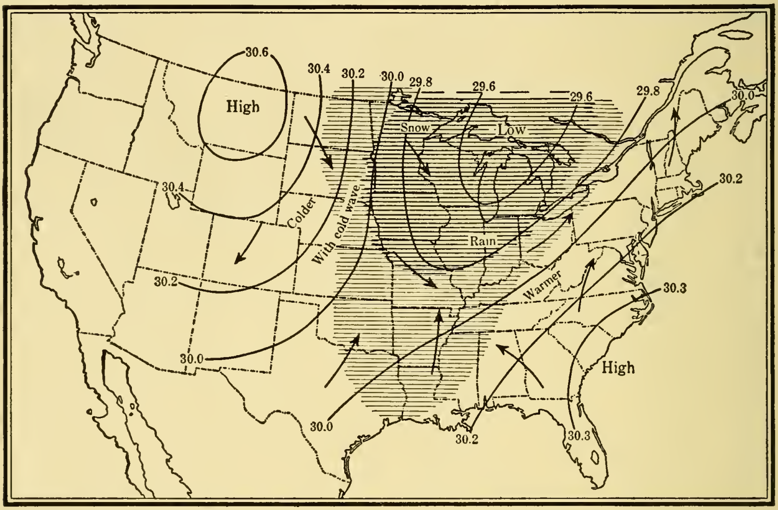

FIG. 9. Winter Storm over the Lake Region (Northern Circuit)

the storm center with northwesterly winds, overspreading the northern tier of states from the Rocky Mountains to the Lakes (Fig. 9). On the third day the storm center usually reaches the vicinity of the Gulf of St. Lawrence, perhaps still further increasing in energy; the area of rising temperatures with snow or rain extends to the Atlantic coast; falling temperatures with clearing northwest winds are noted across the central valleys and to the eastward. Snow, with westerly gales, often continues for some hours at stations on the lower Lakes, and storm warnings of high southwest, west, and northwest winds are frequent under these conditions along the northern Atlantic coast (Fig. 10). As the storm center moves off beyond the range of

the weather map the clearing and colder weather overspreads the northeastern sections. After a day or so the cold begins to moderate over the central valleys, the weather continuing fair until controlled by the next cyclone.

Northwestern storms are not the greatest rain-bringers in the eastern United States. Precipitation is generally light and on their western side until they reach the upper Mississippi Valley

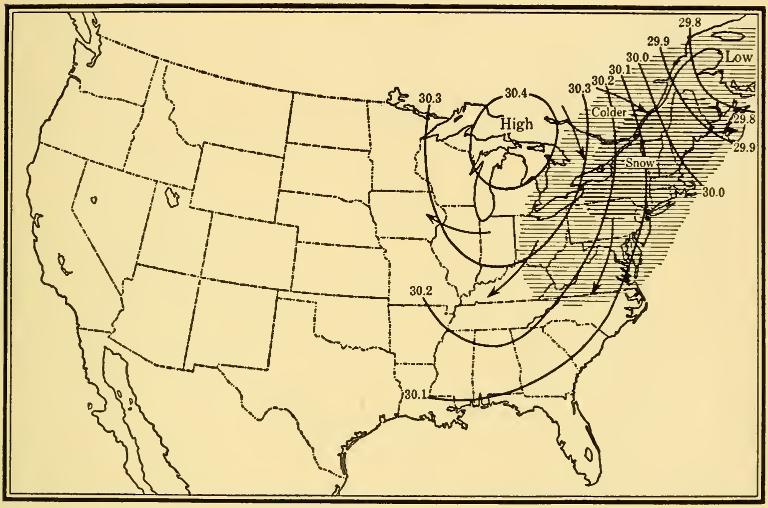

FIG. 10. Winter Storm Passing off to the Northeast

and the Lakes, when the rainfall becomes heavier and is found in the eastern quadrants, especially to the southeast of the center. Further, these storms are generally unfavorable to precipitation over southern sections, which are likely to be outside the limits of rainfall. Extended cyclones of this type, as well as of the other types, may, however, cause stormy weather over practically the whole country east of the Rocky Mountains, carrying their cold and their rains as far south as the Gulf of Mexico. A succession of northern circuit storms tends to cause a spell of dry weather in the south. At the same time the warm southerly winds, flowing northward over the states which lie south of the storm path, bring high temperatures to those sec-

tions. One other feature of this same type of storm is its tendency not infrequently to be accompanied and followed by a generally unsettled condition, extending as a long trough across the central valleys to the Gulf of Mexico. Such a pressure distribution is likely to develop secondary storm centers and to lead to a somewhat prolonged period of dull, rainy, and cloudy weather over eastern and northeastern sections.

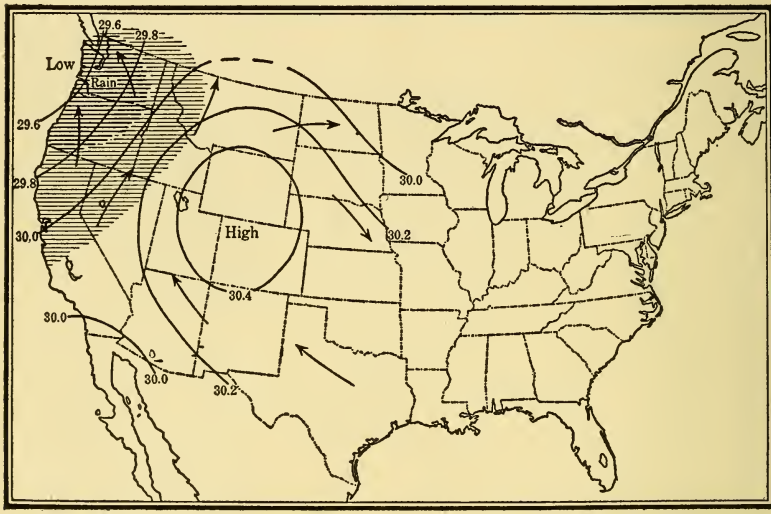

FIG. 11. Winter Storm on the North Pacific Coast

Storms of the North Pacific type which have crossed the northern portion of the Plateau Province and then follow the northern circuit do not differ essentially in the weather types which they produce over the eastern United States from those of storms of the Northwestern type. Fig. 11 illustrates a North Pacific type storm when it is controlling the conditions over the northern Pacific slope before it moves east across the Rocky Mountains. From the northern circuit, in common with a number of storms of the Northwestern type, some of this North Pacific group loop southward when east of the Rocky Mountains, and then turn northeastward to the Lakes and New England. Some North Pacific type lows do not follow

the northern circuit, but loop southeastward over the Plateau, perhaps skirting the Gulf coast on the southern circuit and then moving northeasterly up the Mississippi Valley, or crossing the Rocky Mountains farther north (latitude 35°–45°) and then traveling northeast. Fig. 12 illustrates the larger controls over the weather of the southern Plateau and Rocky Mountain area by a storm which has moved in from the

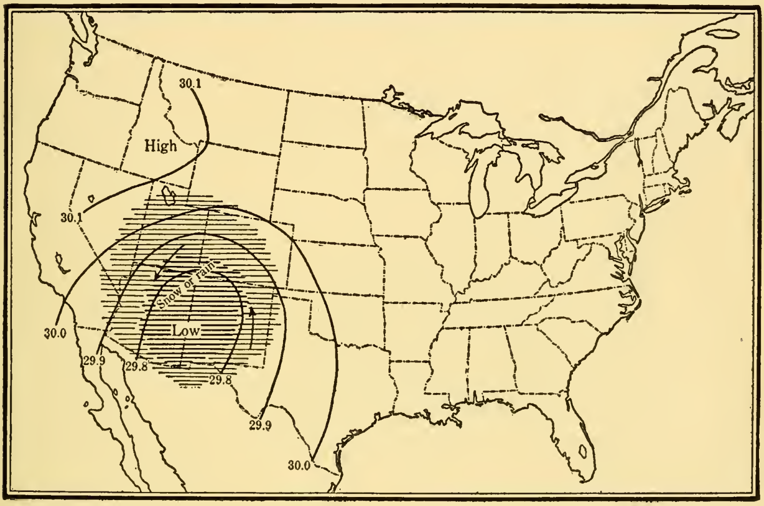

FIG. 12. Storm over Southern Plateau and Rocky Mountain Region

Pacific coast. The regional weather types differ according to the path and the special characteristics of each cyclone. When the storm follows a low latitude, perhaps crossing northern Texas and Oklahoma, or Louisiana, before turning more directly northeast, the tendency is to extend the area of general precipitation over the southern and southwestern Gulf states, as well as over the more northern sections west of the Mississippi River. A more southerly path also usually means that there will be more rain or snow and more cool northerly winds; on the other hand, a more northerly path usually results in less precipitation over the Southern states.

From the western Gulf of Mexico and from Texas comes a

group of cyclones known as the Southwestern, or Texas, type, which develop their essential characteristics in that region. Some of them come from the north Pacific coast, across the Plateau Province; some move in from California; some few perhaps come through Mexico (Fig. 13). Usually moving northeast across the Mississippi, they reach the vicinity of the Lakes or the Ohio valley in about one day, and New England

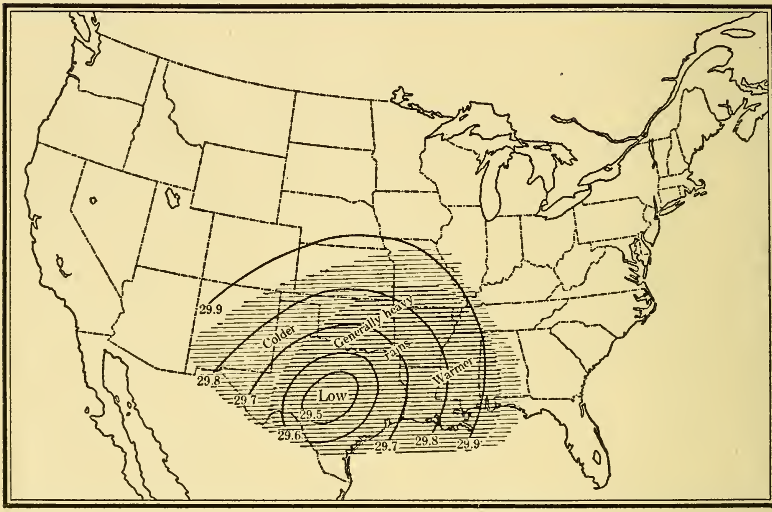

FIG. 13. Southwestern Type Storm Central over Texas

or the Gulf of St. Lawrence in about another day. Some take the outside route, along the Atlantic coast, for a part or the whole of their northward journey. The most typical and best-marked storms of this type come in February and last through March and perhaps into April. Their habit is to increase in intensity and in velocity of progression as they advance northeast. They are preceded and accompanied by a decided rise in temperature and by general and usually heavy rains over the eastern United States, east and southeast of their centers, especially over the Gulf and Atlantic coasts and in the Ohio valley (Fig. 14). When temperatures and other conditions are favorable, heavy snows are frequent to the north and north-

east. The first autumn snowstorm in northeastern sections often comes with the approach of one of these southwestern storms. These storms not only rank as heavy rain-bringers, but also belong, as a whole, among the most severe storms of the eastern United States, with their high winds and their marked temperature-differences between front and rear. The extended rain area of a southwestern storm, having already

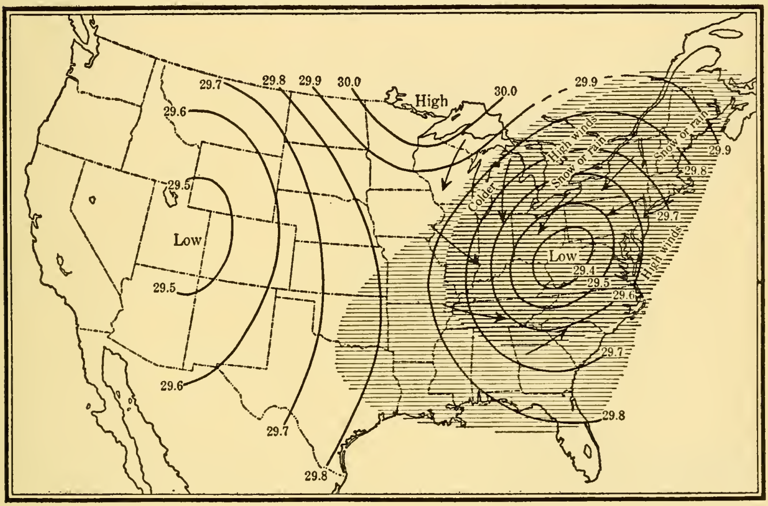

FIG. 14. Well-Developed Winter Storm over the Eastern United States

spread over a considerable section of the Gulf states and even of the Great Plains, may cover the lower Mississippi and Ohio valleys in the first twenty-four hours after the development of the low over the western Gulf, and then reach the Atlantic coast and the New England states in the second twenty-four hours. Over the Great Lakes and the northern Atlantic coast storms of this group begin with northeasterly winds, generally increasing to high velocities and backing to the northwest. Gales dangerous to navigation over northeastern sections are frequent under these conditions, and storm warnings are usual at such times. A high from the northern Plateau or eastern Rocky Mountain slope usually follows the

storm, drifting first south and then northeast, acting with the low to produce the fall in temperature. A marked high on the north Atlantic coast sometimes blocks the storm and changes its path.

Storms of the Colorado type begin their weather controls in the eastern United States by causing unsettled weather with

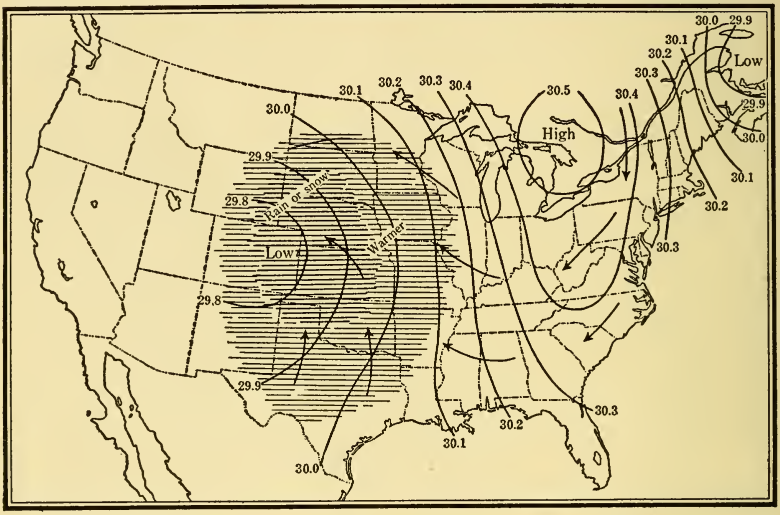

FIG. 15. Well-Developed Winter Storm Central over Colorado

precipitation, which may be in the form of general rains or snows, or of scattering showers or thunderstorms (in the warmer months), over a considerable area between the Mississippi River and the Rocky Mountains. To the north of the center rain or snow falls with northerly winds (Fig. 15). Moving eastward toward the Lakes, these storms usually increase in intensity; their precipitation area advances to the Atlantic coast; they are preceded by rising and followed by falling temperatures. Such a storm may give general rains over a large area east of the Mississippi, with snow in the north, gales, and storm warnings. Often, however, while the rains or snows may be fairly general over the northern half of the country east of

the Rocky Mountains, the precipitation area does not extend into the southern tier of states. There the effect of the storm may be merely to raise the temperatures in front and to cause fair to cloudy weather, followed by clearing and cooler in the rear. Fig. 16 illustrates the general conditions accompanying a well-developed winter storm centered over the Mississippi

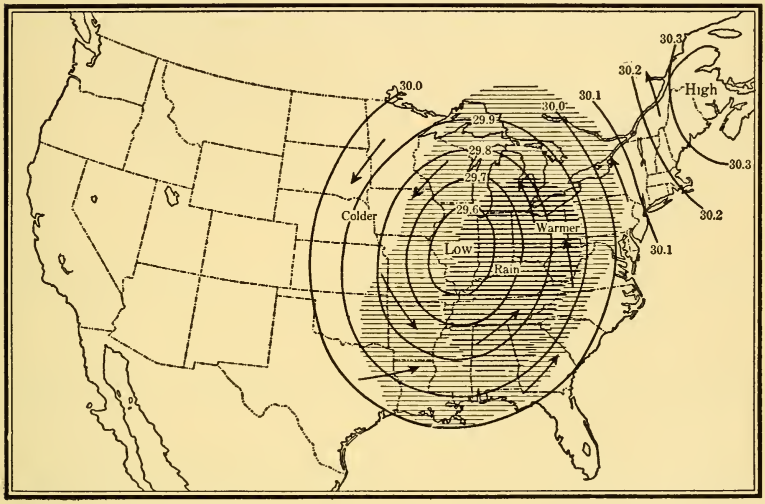

FIG. 16. Winter Storm over the Mississippi Valley

Valley. Such a storm comes from the west or south and moves east or northeast, across or to the south of the Lakes.

Storms moving northeast along the Atlantic seaboard, whether they come from the west or southwest, or first appear on the weather map off the middle or south Atlantic coast, are popularly known as coast storms. While these storms do not, as a rule, cause stormy weather over a large part of the mainland, they are often severe, bringing heavy rains over the eastern Gulf and south Atlantic states and, in winter, heavy snows over northeastern sections, with gales changing from easterly to westerly at sea and along the coast (Figs. 17 and 18). When snow falls these high winds are a serious handicap to the rail-

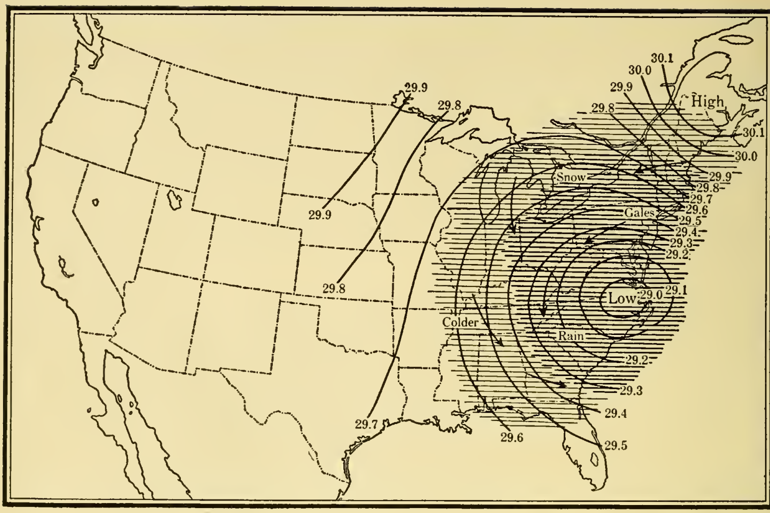

FIG. 17. Severe Winter Storm over the Atlantic Coast

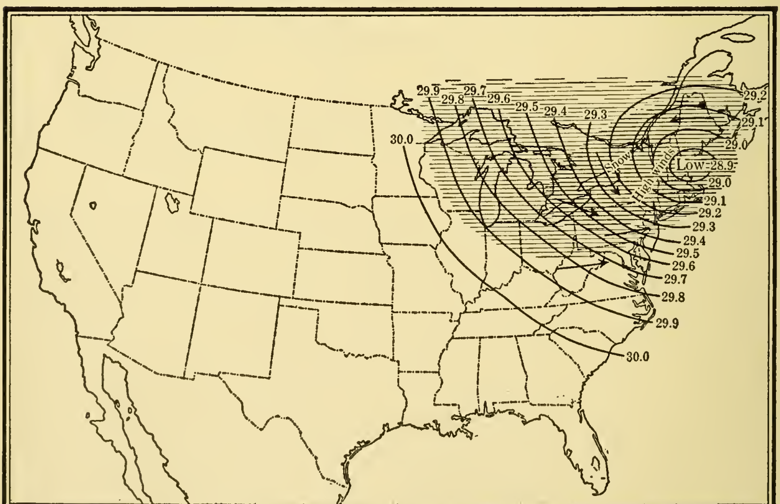

FIG. 18. Severe Coast Storm over New England (Winter)

roads and to electric car lines because of the heavily drifting snows. Coast storms are usually followed by rapidly falling temperatures, with high northwesterly winds.[1]

Weather is not always dominated by low pressure conditions. Not infrequently an immense area of high pressure may cover most of the country, in summer as well as in winter, and clear or fair weather prevail over practically all sections, with

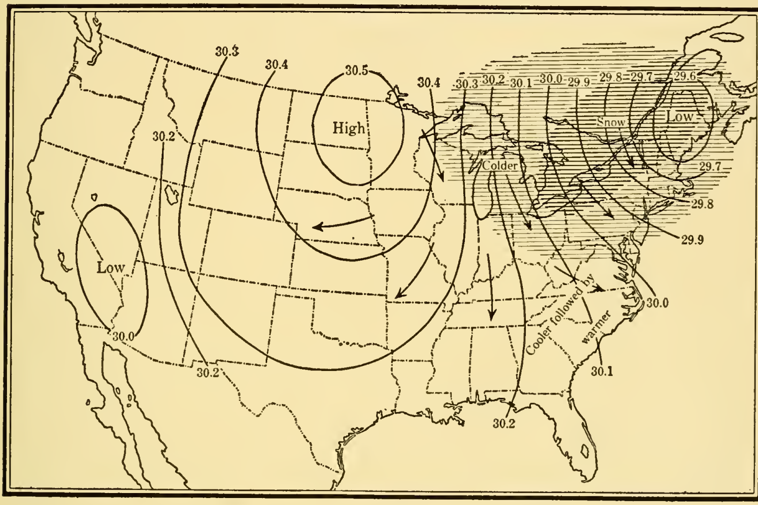

FIG. 19. Dominant Winter Anticyclone

more or less marked typical diurnal variations in temperature. In spring and autumn such conditions are often favorable for frost. Fig. 19 illustrates the far-reaching influence of an im-

[1] For other studies of cyclonic control over precipitation see W. G. Reed, "The Cyclonic Distribution of Rainfall in the United States," *M. W. R.*, Vol. 39 (1911), pp. 1609–1615; C. F. Brooks, "The Distribution of Snowfall in Cyclones of the Eastern United States," ibid., Vol. 42 (1914), pp. 318–330; W. R. Eckardt, "Luftdruckverteilung, Zyklonenzug, und Regenfall in Nordamerika," *Met. Zeitschr.*, Vol. 40 (1923), pp. 149–150. Other references are H. H. Clayton, "Relation of Clouds to Cyclones and Anticyclones," *Annals Astron. Obs. Harv. Coll.*, Vol. 30, Part IV (1896), pp. 366–376, Plates II–V; J. A. Udden, "On the Cyclonic Distribution of Rainfall," *Publ. Augustana Coll. and Theol. Sem.* (Rock Island, 1905), 25 pages; T. A. Blair, "Local Forecast Studies—Summer Rainfall," *M. W. R.*, Vol. 49 (1921), pp. 183–190; idem, "Local Forecast Studies—Winter Precipitation," ibid., Vol. 52 (1924), pp. 79–85.

mense anticyclone central over the northern Plains. After the disappearance of the retreating cyclone in the northeast, the anticyclonic control becomes dominant over practically the whole country.

Winter Weather Types of the Eastern Climatic Province. The general series of weather changes during the passage of a well-developed winter cyclone and a following anticyclone over the eastern United States in winter is about as follows: a gradual clouding in advance of the storm; increasing northeasterly, easterly, or southerly winds; rising temperature, often bringing unseasonable warmth and even resulting in a thaw in northern sections; rain or snow; a change in wind direction to westerly and falling temperature, with clearing weather. If the cyclone and anticyclone are near, well developed, and moving rapidly, this sequence is well marked, the wind changes are distinct, the wind velocities are high, the temperature variations are sudden and large, and the precipitation is heavy. On the other hand, all the characteristic weather types are weakened, and may attract little attention, if the cyclonic control is weak or distant. The types also vary with the location of a district to the north or south of the storm path.

In the eastern United States the cold wave is the most striking and most characteristic winter phenomenon.[1] When storms move rapidly the southwestern quadrant is usually considerably warmer than the northeastern, the northwestern being the coldest. In a good typical winter case the average temperature east of the Mississippi River and south of the storm center was 59°; to the west and south of the center it was 35°; in the northwest quadrant it was 15°. From a large number of observations the writer has determined the temperature departures in the four quadrants of well-developed winter cyclones in the eastern United States. Taking the temperature at the center as the standard, the average departures were as follows: northwest, −8.7°; northeast, −5.6°; southeast, +7.3°; southwest, +26°. For winter anticyclones the results were: northwest, −5.1°; northeast, −3.3°; southeast, +8.9°; southwest, +7.0°. In general, the average rise

[1] See Chapter XVI.

of temperature in front of a winter storm in the eastern United States is not far from 10°, but may reach 20° to 30° above the seasonal normal. Stations which happen to be on the northern side of a passing cyclone have northerly instead of southerly winds, and therefore do not experience such marked temperature changes as are noted at stations south of the storm path.

Summer Weather Types of the Eastern Climatic Province. Summer weather in the eastern United States is generally peaceful and uneventful. It is frequently marked by periods of stagnation of the lows and highs A weak summer cyclone, usually without a widespread cloud area, passes slowly along the northern circuit, while an area of high pressure is central over the middle or southern Atlantic coast. On the northward gradients in front of the approaching low is a belt of warm, muggy, southerly winds, which spreads eastward as the low advances. The temperature rises higher each day for several days in succession.[1] Thunderstorms following the increasing growth of cumulus clouds are common during these hot southerly spells, especially at the time when the winds in the rear of the retreating low shift quickly to northwesterly.[2] Under these latter conditions there follows a welcome fall in temperature in the brisk, cool, northwesterly winds. The high advances from the west. The winds soon decrease in velocity. There comes a short spell of clear and cool weather, with marked diurnal variation of temperature, giving pleasantly refreshing nights. Occasional showers may fall on the margins or toward the center of the high, and soon the approach of another cyclone starts the whole succession of weather types over again. Variations on the general theme occur as the cyclonic and anticyclonic controls differ in each case. There are no two series of these weather types exactly alike. That fact adds an interest to weather study which frees it from all trace of monotony.

In summer most of the rain over the eastern United States falls sporadically in thunderstorms, which are especially large and well developed from the Mississippi Valley to the Atlantic.

[1] See Chapter XVII.
[2] See Chapter XIV.

While these thunderstorms are usually of short duration, they are often violent and give heavy rainfalls in a short time. A summer month with heavy rainfall is likely to be a month with numerous and well-marked thunderstorms. It must not be supposed that general storm rains are entirely absent from the eastern United States in summer. Widespread and severe cyclonic storms are rare; but occasional lows, on whichever path they travel, may give general precipitation, especially over the Northern states east of the Mississippi River but also extending into the middle tier of states to the south. Such general rains are often most beneficial agents in breaking a long spell of drought over the great wheat and corn belts of the West.

Spring Weather Types of the Eastern Climatic Province. Spring weather types are, as has been noted, transitional between winter and summer. Thus in late winter or early spring a pressure distribution of the hot wave type is a clear indication of the coming of warm-season conditions. Occasional cyclones from the south, with chilling northeast winds and cold rains or snows in eastern sections, are unpleasant reminders that winter has not wholly lost its grip. Especially severe are such storms when the southern low unites with a low coming east on the northern circuit, the two joining somewhere on the northern Atlantic coast and giving high winds and heavy precipitation, which may be snow or rain according to the temperatures. If such a storm comes to a standstill on the coast, as happened in the case of the famous "March blizzard" of 1888, the resulting precipitation is unusually heavy. Winds from the cold continental interior bring wintry temperatures at intervals in the midst of warm, spring-like weather types. It is in the northeast that winter lingers longest, about the cold waters of the Great Lakes and in northern New England. Destructive spring frosts suggest weakening winter controls, but April showers, often really nothing but embryo thunderstorms, presage summer.

Autumn Weather Types of the Eastern Climatic Province. Autumn brings many of the most satisfying days of the whole year — bright, clear, bracing days, under high pressure con-

trol, with warm noon hours followed by crisp, even chilly nights; with frequent autumnal frosts of increasing severity and the characteristic nocturnal valley and lowland fogs of the colder season. There are few more glorious spells of weather than the so-called Indian summer.[1] Real summer spells these are, wedged into the midst of the storms which are then becoming increasingly frequent and severe and of cool waves which are soon to become cold; delaying, temporarily at least, the advance of winter.

Autumn cyclones, most of them following the northern circuit, take on the winter habit of greater violence and of more rapid progression over more southerly latitudes. Not a few of them, however, still bear the summer earmarks of a deficiency of precipitation, but their inflowing winds of increasing velocity and their extended cloud sheets and general rains or even snows make it more and more difficult for the sun to control the temperature. Gales and the number of rainy days increase over the Great Lakes and in northeastern sections, because those districts are near the storm centers whose control does not extend as far southward as is the case later in the season. General cyclonic storms, characteristic of winter, show an increasing control over weather as early as September, and to this fact is probably due the widespread but mistaken popular belief in an "equinoctial storm."

The West Indian hurricanes of autumn, although smaller, are more highly developed and more severe than most of the cyclones which affect the United States. They usually cause violent gales and heavy rains along the Atlantic and Gulf coasts, and are destructive to shipping interests and even to buildings. Fortunately for interior sections their influence does not extend far inland. The total annual rainfall at many of the stations in these southern coast districts is markedly affected by the occurrence or non-occurrence of tropical hurricanes. When a West Indian hurricane joins, by means of a long trough of low pressure, with a storm from the Great Lakes off the middle or northern Atlantic coast, unusually severe storm conditions are sure to follow, especially along the New England

[1] See Chapter XVII.

coast. A high following closely on the rear is likely to bring rapidly falling temperatures, with snows, in late autumn. In general, however, the temperature changes accompanying West Indian hurricanes are much less emphatic than those which are characteristic of winter cyclones, because the former occur near the coast and in the warmer months. Fig. 20 illustrates the generalized weather conditions associated with a West Indian hurricane on the south Atlantic coast, moving northeastward.[1]

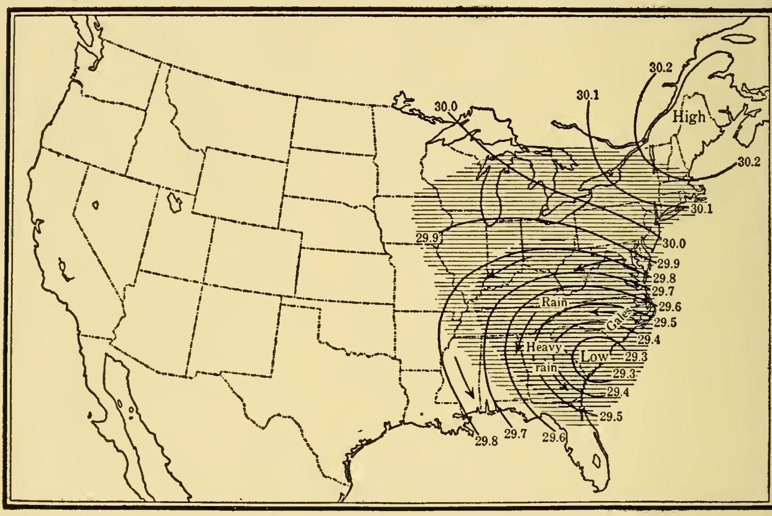

FIG. 20. West Indian Hurricane on the South Atlantic Coast

Curves Illustrating Weather Types of the Northeastern United States. The characteristics of some of the more common weather types of the eastern United States may be better appreciated through an examination of a series of curves selected to illustrate typical conditions of frequent occurrence. These curves were recorded on the thermograph and the barograph of the Jackson Company at Nashua, New Hampshire, a representative New England station, and were chosen because New England, as a result of its peculiar position in relation to cy-

[1] See also E. B. Garriott, "Monthly Statement of Average Weather Conditions," *M. W. R.*, Vol. 28 (1900), pp. 342, 395, 430, 483, 538–539; Vol. 29 (1901), pp. 21, 57, 117–118, 163, 208–209, 258, 307.

clonic paths, offers unusually favorable opportunities for studying cyclonic control of weather and climate.[1] If a series of similar curves were provided for different stations in other parts of the United States, the teaching of local climatology would be greatly simplified, stimulated, and improved. Each weather type has its own special and characteristic economic and human responses. An understanding of these types is often of great help in making individual weather forecasts for two or three days ahead, and in preparing oneself to guard against the unfavorable effects of the different types, as well as to profit by the favorable effects. As any such type curves remain type curves whenever they are recorded, the year of occurrence obviously matters little. The curves are arranged by seasons, beginning and ending with winter, and the conditions illustrated are noted in the legend accompanying each figure. Similar illustrations of cold waves and of hot waves will be found in Chapters XVI and XVII respectively.

Each Section has its Own Weather Types. The accompanying curves relate to one station only, in New England, but the weather types which they illustrate are found, more or less modified, over most of the eastern United States. In the Southern states, with increasing distance from the most frequented cyclonic paths, the storm control is naturally weaker; the diurnal phenomena are more marked and more characteristic, even in winter, and the changes in winds and temperature are less sudden, less frequent, less violent. Thus, for example, in winter, during the passage of a well-developed cyclone along

[1] The illustrations are from material in the Climatological Laboratory of Harvard University whose preparation was originally suggested by Professor W. M. Davis. The state of the sky is indicated along the thermograph curves. The wind direction is shown along the barograph curves. The distance between the broken lines which join the crests and the troughs of the thermograph curves shows the amount of the diurnal range (or change) of temperature. The belt inclosed between these lines (temperature belt) rises and falls with the cyclonic or anticyclonic control of the temperature. Although pressure is not an element of importance in climatology, the barograph curve when employed in such diagrams as these is a great help in showing the extent and duration of the successive cyclonic and anticyclonic controls. Such diagrams offer abundant and varied exercises for discussion in laboratory work and give a clearer and more accurate view of the complexity of our climates than can be obtained from any of the normal climatic tables (Figs. 21–31).

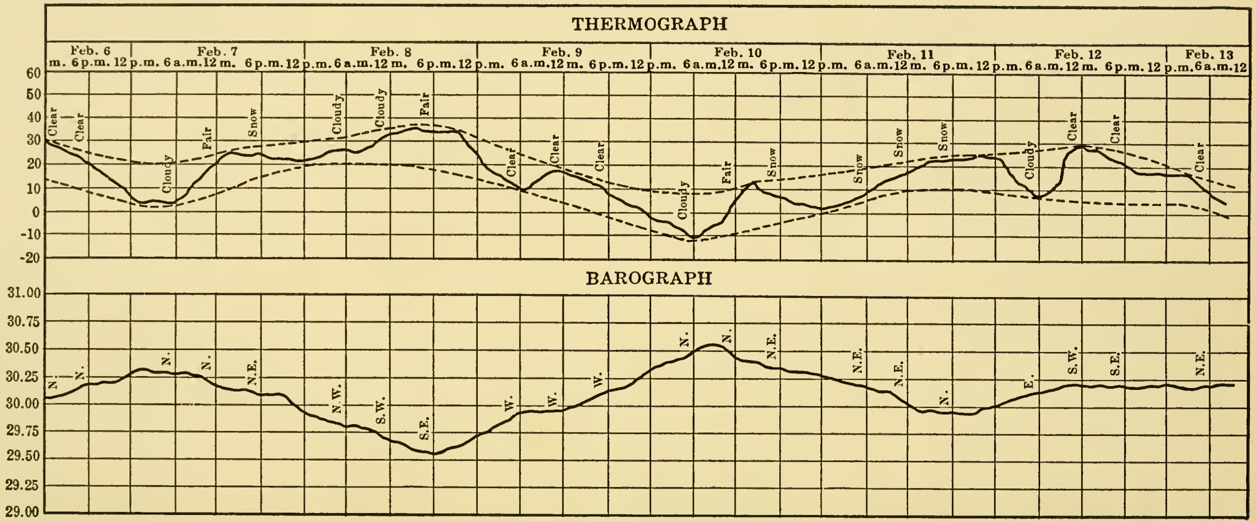

FIG. 21. A Week of Winter Weather

the northern circuit, the Southern states may have all their winds from a southerly direction with but little cyclonic control of temperature, while the more northern states have a sudden shift from southerly to northwesterly winds with a cold wave. Again, the cloud and rain areas of cyclones crossing the northern tier of states often do not extend as far as the southern stations. The latter, therefore, have clear or fair weather, or perhaps a brief shower, while farther north there may be heavy and long-continued rains. In winter it very frequently happens that snow falls in the north while the higher tempera-

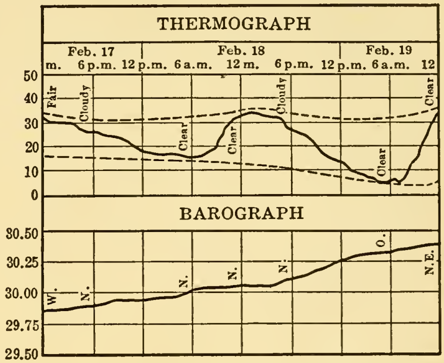

FIG. 22. Diurnal Temperature Range in Winter Anticyclone

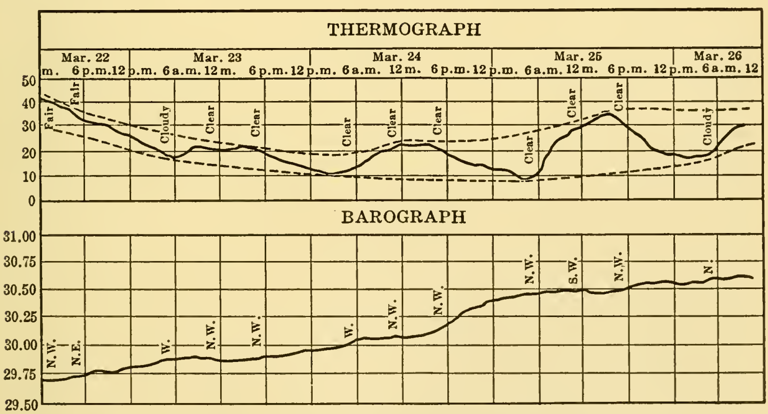

FIG. 23. Cyclonic and Anticyclonic Weather in Early Spring

tures of the lower latitudes bring rain instead of snow. The chilling northeast winds felt on the north Atlantic coast when a cyclone is approaching from the south are not experienced far inland or far south. Again, in summer it is likely that the north-

ern tier of states will enjoy the cool waves which come on the rear of weak summer cyclones, while farther south there is no break

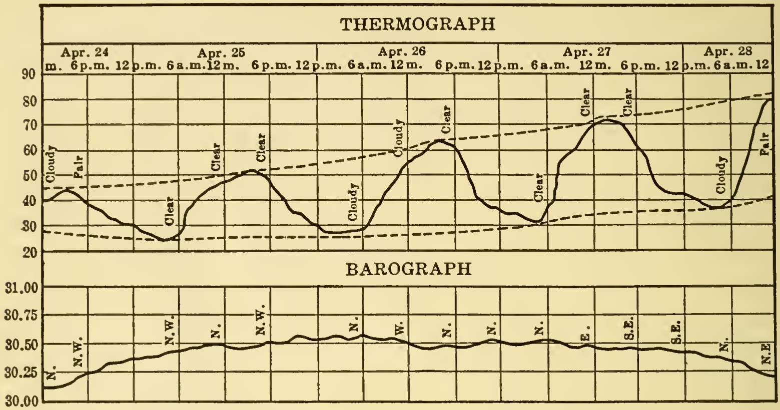

FIG. 24. Warm Days and Cool Nights in April

in the heat brought by the southerly winds. Modifications such as those here suggested, and many others, result from

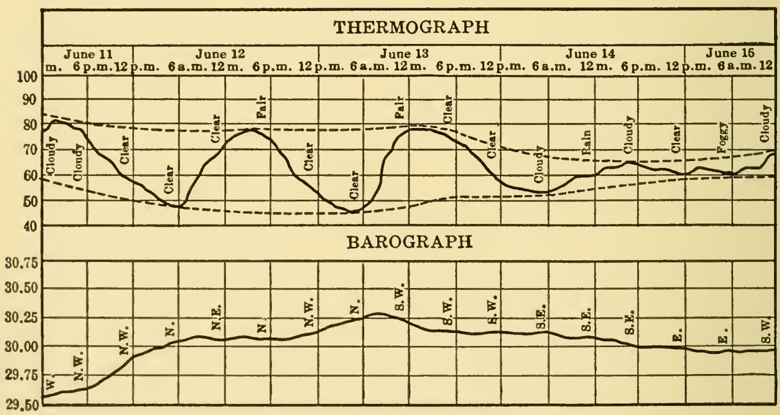

FIG. 25. Anticyclonic and Cyclonic Weather in June

differences of latitude, of topography, of exposure to winds from the ocean or the Gulf or the Great Lakes, of altitude, and from numerous other controls. Each district has its own varieties of weather types. The almost endless series of modifi-

cations as they occur in other sections of the country cannot be further discussed in this chapter.[1]

Winter Weather Types of the Pacific Province.[2] The winter and summer types on the Pacific slope are as strongly contrasted as those in the East, although they differ considerably from them.[3] All winter long a procession of storm areas keeps moving eastward across the northern Pacific slope, generally following the international boundary fairly closely to beyond the Rocky Mountains and continuing thence on the usual paths. Temperatures about normal; mild southerly winds; rains over Washington and Oregon; cloudy weather and showers perhaps extending into California as far as San Francisco, or beyond,— these are the usual conditions when a winter storm is over Washington or Oregon.[4] With steep gradients, southerly gales occur along the coast from Cape Mendocino to Vancouver Island, and brisk southeasterly or southerly winds in Oregon and Washington. Rain usually begins with southeasterly winds, continuing as the wind veers to south, southwest, and west. When, less frequently, the cyclonic center moves farther south,

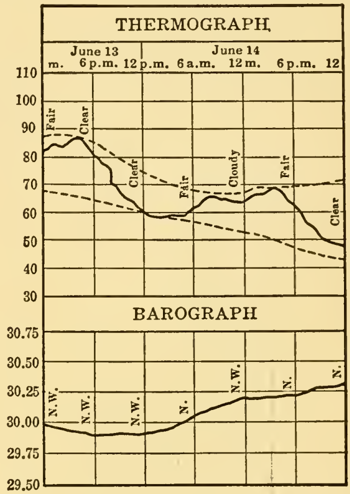

FIG. 26. Summer Cool Wave

[1] A. J. Henry has given some very instructive curves to illustrate the effect of a difference of latitude upon the weather conditions at five stations situated on the same meridian. (*U.S. Weather Bur. Bull. Q*, Figs. 1–3, pp. 16–18.) W. M. Davis has presented an excellent description of New England weather types in *Annals Astron. Obs. Harv. Coll.*, Vol. XXI, Part II (1890), pp. 116–137.

[2] The writer is indebted for helpful criticisms on these sections to Messrs. E. A. Beals, F. H. Brandenburg, Ford A. Carpenter, Alexander McAdie, and William G. Reed.

[3] B. S. Pague and S. M. Blandford, "Weather Forecasting and Weather Types on the North Pacific Slope," Portland, Oregon, 1897; W. A. Glassford, "Weather Types on the Pacific Coast," *Cal. Acad. Sci.*, *Bull. 5* (August 31), 1886; Dean Blake, "Anticyclonic Weather in California," *Bull. Amer. Met. Soc.*, Vol. V (1924), pp. 127–128 (abstract, with discussion).

[4] See Fig. 11.

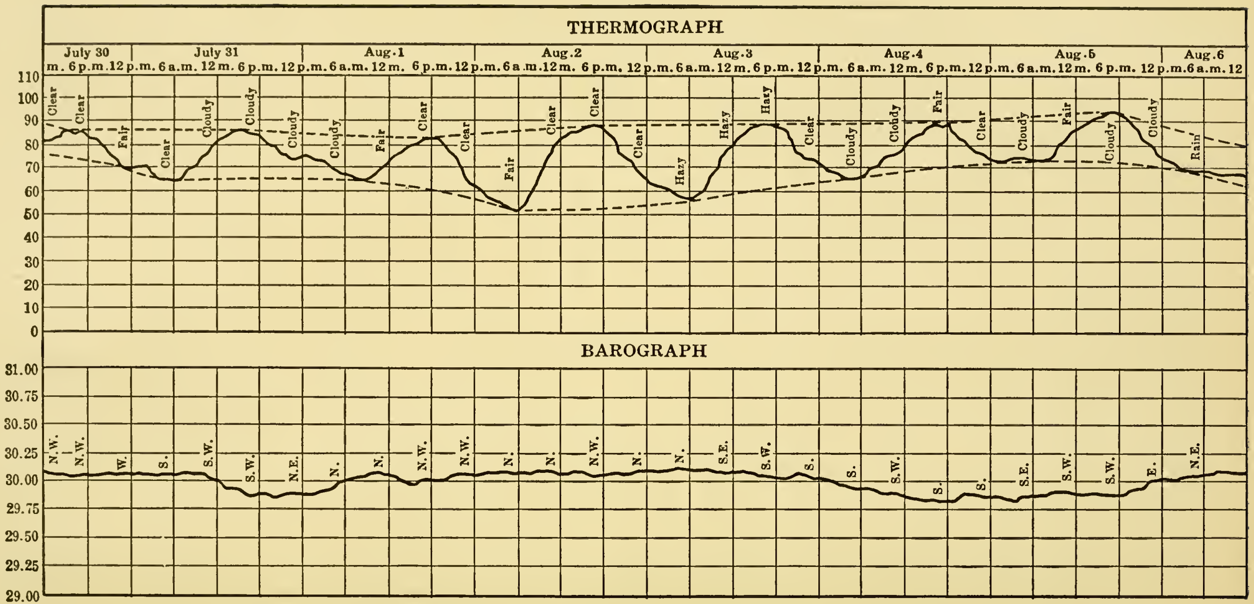

FIG. 27. Summer Week of Moderate Temperature

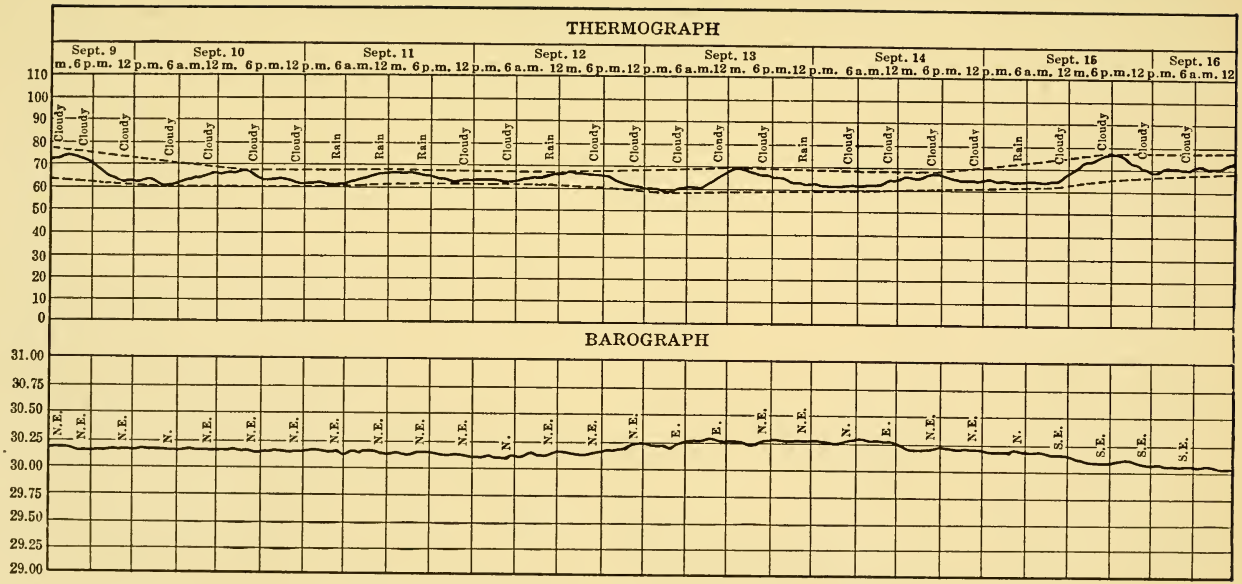

FIG. 28. A Week of Clouds and Rain in September

northerly winds and clear weather prevail over the northern districts. Winds from the northern quadrants are likely to be fair-weather winds at all seasons. The greater the distance of

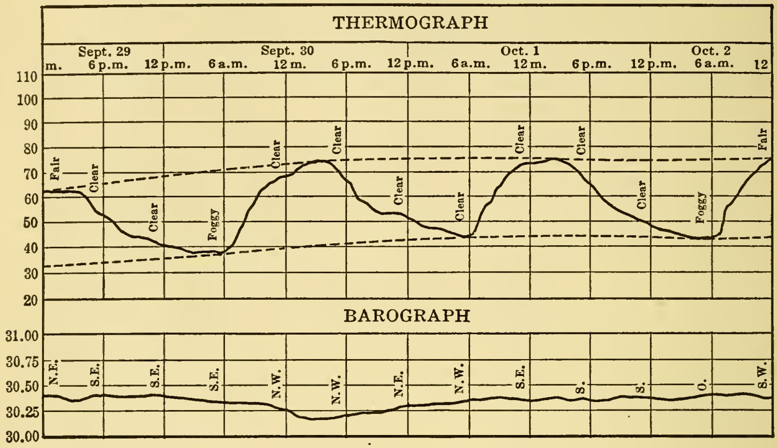

FIG. 29. Typical Fine Days in Early Autumn

the storm center, the less is its control over the weather. At San Diego, for example, perhaps less than one tenth of the storms which cross the northern section of the Pacific coast have any notable effects. California therefore has less rain and cloud than prevail in Washington and Oregon, and southern California has even less rain and more sunshine than the northern portion of that state. Well-developed low pressure areas are rare in southern California. Storms entering the southwestern portion of the state usually give light rains along the coast, and an occasional depression over the southern interior may cause rains of

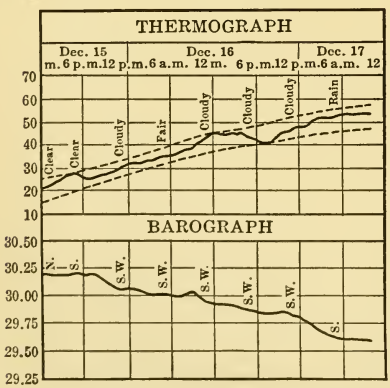

FIG. 30. Cyclonic Control of Winter Temperature Change

relatively large amounts. The name "Sonora" has been applied, in a rather loose way, to certain winter and spring cyclonic storms which bring rains in southern California.[1]

During the winter the prevailing movement of anticyclones is from the California coast in the vicinity of Cape Mendocino northward to about latitude 45° N., crossing northern California and southern Oregon to southern Idaho. There they become stationary, or disappear, or move farther east. Other anticyclones come from the north of Montana and move southeasterly toward the Mississippi Valley. When the typical winter low is over the northern Pacific coast there is usually a high central in Utah or western Colorado. A marked anticyclone, with low temperatures, fairly stationary north of Montana and spreading westward toward the coast, retards the eastward movement of the north Pacific coast cyclone. The result may be rain of several days' duration west of the Cascades, and perhaps snow with freezing temperatures east of these mountains. If the cyclone is forced southward along the coast to the mouth of the Columbia River, and even much farther south, there comes a great flow of cold air from the interior, from the north and northeast, which descends the western slopes of the Sierra Nevada and Cascades into the valleys of Washington, Oregon, and California. Heavy snows fall east of the Cascades as far as Idaho, followed by fair, cold weather over the Pacific coast generally, except on the seaboard. Occasional snows may then fall in western Washington and Oregon, and even on the coast, with northeast winds and low temperatures. With the disappearance of the low to the south,

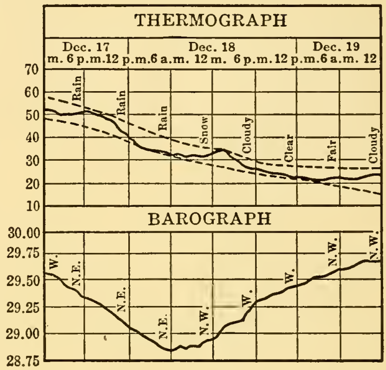

FIG. 31. Irregularity of Occurrence of Maximum and Minimum Temperatures in Winter

[1] The "Sonora" thunderstorms of southern California and of the Southern Plateau Province are referred to in Chapter XIV.

the temperature slowly rises and the snow ceases, but there is no general warming until another cyclone arrives, causing strong winds. These northeasterly winds are the coldest winter winds, but they are of relatively infrequent occurrence.

Sometimes the low may be forced southeastward over California, bringing general and severe storm conditions in that state, with heavy rains, gales, floods, and washouts. An area of high pressure over the northern Pacific coast or over the Great Basin, with lower pressure in southern California, brings prevailingly clear weather and dry air (except for local rains in the far north), warm days, and relatively cool nights. Under such a distribution of pressure, when the gradient is but moderately steep, northers occur in the valleys of California, extending southerly (Chapter XVIII).

There are, of course, many subordinate types of high and low development and movement, each of which has its own characteristic control over the weather. The general character of the winter precipitation on the Pacific coast obviously depends upon the paths followed by the winter storms. The farther south the cyclones move and the more intense they are, the heavier and the more widespread is the rainfall.[1]

Summer Weather Types of the Pacific Province. From a stormier winter to a drier, more settled, and fairer summer, the change on the Pacific slope is in general accord with that which takes place the country over. Northward swings the winter

[1] Two general laws covering the conditions of winter precipitation on the Pacific coast, especially in California, have been deduced by McAdie ("Monsoon and Trade Winds as Rain Makers and Desert Makers," *Geogr. Rev.*, Vol. 12 (1922), pp. 412–419) and have commended themselves to Henry ("Seasonal Forecasting of Precipitation — Pacific Coast," *M. W. R.*, Vol. 49 (1921), pp. 213–219). According to the first law, when the continental anticyclone is over Oregon, Idaho, Utah, and Nevada, the winds are generally northeast or north, the individual cyclones cross the northern sections, and there is generally fair weather with little precipitation. According to the second law, when the Aleutian low extends well to the southward along the Oregon coast, and the continental high is centered over Saskatchewan and Montana, the surface air movement in California is from southeast or south. Unsettled weather is then the rule, accompanied by heavy rain west of the Sierras and by heavy snows in the mountains themselves. The individual moving lows, first appearing over Vancouver Island and the northern Washington coast, deepen and extend southward. In about twelve hours the rains extend to northern California; in twenty-four hours they reach the central coast, and in thirty-six hours the coast south of Point Concepción.

storm belt. Northward moves the cyclonic rain belt. The summer cyclones, traveling east along a higher latitude, cannot greatly influence Pacific coast weather. They often cause cloudiness without precipitation, but once they have passed beyond the western mountains they are practically negligible so far as the coast is concerned. The rains diminish as summer approaches. By midsummer absolute dryness prevails over

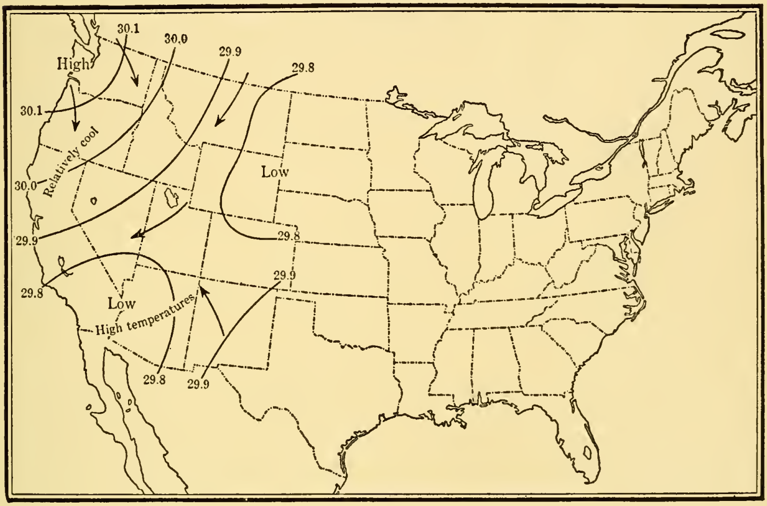

FIG. 32. North Pacific Summer Anticyclone

much of the southern portion of the area. A characteristic of the warmer months is the presence of a more or less enduring anticyclone over the northern or northwestern Pacific coast, while a permanent low extends from the Gulf of California into the Basin region (Fig. 32). Hostile to rainfall this pressure distribution certainly is. A summer dry season is the inevitable result. Settled weather, with cool mornings and nights and warm afternoons; light and local showers rather than general rains, and even these showers limited to northern sections and to the mountains,—thus, in the briefest possible way, the summer of the Pacific slope may be characterized. The prolonged rainy and cloudy spells and lower temperatures of winter

give way to pleasanter, although occasionally uncomfortably warm, weather types. Yet the high day temperatures under the strong sunshine of the inland sections are accompanied by low relative humidities, and the sensible temperatures are therefore low. There is a general absence of oppressive muggy heat inland, and the coast temperatures are distinctly cool. Summer showers in northern sections come from lows passing east of the Rocky Mountains whose weather control extends westward on their rear, or from a weak cyclone which forms over the great valley and afterward unites with another low over British Columbia. Thunderstorms, of frequent occurrence in eastern Oregon, eastern Washington, and Idaho, are rare in the western portions of those states and in California, except in the higher portions of the Sierra Nevada and of the desert.[1] They occasionally occur in summer in the northwestern, western, or northern quadrants of a low passing northeast from the central valleys of California to northern Idaho. Fogs along the coast with high temperatures prevailing in the interior are a notable summer type.[2]

In summer the characteristic movement of anticyclones is northward along the coast from Cape Mendocino to Vancouver Island (about latitude 50° N.), and then easterly along the same path as that of the winter lows. Moderate anticyclones do not, however, dominate conditions to the eastward, as they seem to break up in the interior. As a high approaches, the north Pacific coast has cooler weather, with increasing cloudiness in Washington and Oregon, and perhaps showers west of the Cascades. Decreasing cloudiness and higher temperatures prevail when the center is north of the mouth of the Columbia River. As the high passes eastward across the Cascades the sky clears and the temperature rises, the maximum being recorded when the center is to the northeast. Hot, dry winds, occasionally injuring crops in Washington and Oregon, may occur under these pressure conditions, the warmest summer winds being north or northeast. When the anticyclone is well marked over the north, and there is a well-developed low in

[1] See Chapter XIV.
[2] See Chapter XIII.

southern California, hot northerly winds occur in the Sacramento and San Joaquin valleys.[1] The sequence of weather changes accompanying the progression of a summer anticyclone from the coast of California to beyond the Rocky Mountains usually occupies about five to seven days. When these characteristic summer types of pressure distribution are later than usual, spring is retarded, and farming operations are delayed in northern sections. On the Pacific slope, as elsewhere, there is much weather which is not associated with any very definite cyclonic or anticyclonic conditions. Such types are intermediate, of a more or less nondescript character.

Winter Weather Types of the Plateau Province. The extended region between the Rocky Mountains and the Sierra Nevada-Cascades also has its own individual weather controls and weather types. In winter, especially in December and January, while much of the rest of the country is having unsettled and stormy weather, this western province, together with the Rocky Mountain districts generally and the Plains, may have days and even weeks of fine, cold, dry weather, with generally light winds and marked diurnal variations of temperature, under the control of a persistent, stagnant anticyclone which stands in the way of storms advancing from the Pacific Ocean while a series of highs and lows passes along its eastern edge. Snow or rain falls around cyclones of the North Pacific type following the northern circuit across the Columbia Plateau, or in connection with those which cross the central or southern parts of the district on their eastward journey. The former being the more numerous, the northern portion of this province has heavier precipitation than the southern. The total precipitation which falls from such storms is, however, generally light, as the rain-shadow effect of the Pacific coast mountains and the generally effective inclosure of the whole province would lead us to expect. The inflowing air currents lack the plentiful supply of water vapor which is characteristic of cyclonic circulation in the east or on the northern Pacific coast. General cloudiness, rains, or snows over the southern portion of the interior province come in connection with a

[1] See Chapter XVIII.

cyclone which covers that district and is delayed in its eastward progress across the Rocky Mountains. The area of clouds and of precipitation may also include the central and southern Rocky Mountain region. Cold waves are less frequent and less severe than over the region east of the Rocky Mountain barrier.[1] A low passing across the southern part of the Great Basin region followed by a high which moves southward over Idaho and Utah may bring killing frosts as far south as southern Arizona. The conditions of falling temperature move from north to south, often very rapidly, and may extend from the Pacific coast across the Rocky Mountains. When this air drainage is marked, the freezing line may extend as far south as the citrus region of California. High winds occur in winter and spring on steep cyclonic gradients.

Summer Weather Types of the Plateau Province. In place of the characteristic more or less permanent winter anticyclone, the summer conditions over the Plateau Province are marked by the presence of a fairly permanent and ill-defined low over the lower Colorado region—the so-called Yuma low. Anticyclones from the northwest temporarily interfere with this cyclonic control, and tend to emphasize the effect of this low, but the latter reëstablishes itself as the highs move eastward. In fact it is a sign of spring when the winter Rocky Mountain high pressure area weakens and the low from the Gulf of California establishes itself. Summer weather over this great interior province is characteristically fine and settled. Day after day the same uniform conditions prevail, especially in the southern section. Temperatures are high, notably so in the south and at lower levels, but the greater elevations enjoy cool nights, although the days are hot. The strong diurnal ranges of temperature characteristic of this mountain and plateau country, with the prevailingly bright sunshine and dry air, may easily bring frost on the higher elevations during the clear nights of spring and early summer. Rainfall is generally light, the summer cyclones being weak and ineffective as rainbearers. In the south, over southeastern California, Arizona, southern Utah, and southern Nevada, there is a more or less

[1] See Chapter XVI.

marked summer maximum, known locally as the "rainy season" and usually beginning early in July.[1] These rains are essentially local thunderstorm rains, although they occur in connection with the general cyclonic trough of low pressure. Thunderstorms in Idaho come with the advance of low pressure areas from the northern interior of California.

Winter and Summer Weather Types of the Plains Province. The Plains share to some extent in the weather types of the two regions which join them on the east and on the west. The great permanent winter anticyclone west of the Continental Divide, referred to in a previous paragraph, extends its influence over the Plains area, giving much clear and settled winter weather. The temperatures east of the Divide, in the western Plains area, are usually mild under this anticyclonic control, with a succession of relatively dry, warm, and bright sunny days, the prevailing winds then being westerly, across the Divide. At the same time it is intensely cold to the west of the mountains in the region dominated by the high. But the procession of winter cyclones keeps marching across the Plains chiefly in the north, and cold waves, gales, snows, and blizzards sweep over the area. Sometimes the cyclones loop far south, and severe conditions reach into New Mexico and Texas, damaging southern crops and causing losses of cattle. Some of the storms of the Great Central Valley and the eastern United States come from the southwest and cross the Continental Divide in New Mexico. These lows give to the Plains region heavy snows; and with the eastward movement of the cyclone, cold air from the Canadian Northwest sweeps southward along the eastern side of the Continental Divide. Colorado type storms may bring general cloudiness and precipitation over much of the Great Plains district (Fig. 15). In summer the Plains share with the rest of the country long spells of settled diurnal weather, with hot waves and drought not infrequently extending over many days or even weeks, with thunderstorms bringing local temporary relief, and with occasional general storms bringing more widely distributed and beneficial rains. Easterly winds, climbing the mountain slopes toward the lower

[1] See Chapter IX.

pressure areas of the Plateau Province, give summer precipitation over the mountains to the west of the Plains. Well-defined cyclonic areas are not common over the central and southern Plains, and comparatively few cross the Continental Divide in the southern United States. Weak low pressure areas which succeed in reaching the eastern slope usually move northeast, developing as they travel eastward.

The foregoing description and illustration of some of the more important seasonal and regional weather types is manifestly incomplete and superficial. It is only by means of a careful examination of the daily weather maps, season by season and year by year, that the student of the climatology of the United States can really make himself thoroughly familiar with these types. The suggestions here made may aid in such a detailed investigation.

CHAPTER V

TEMPERATURE

THE LARGER TEMPERATURE RELATIONS · AVAILABLE TEMPERATURE CHARTS · MEAN ANNUAL TEMPERATURES · MIDWINTER TEMPERATURES · MIDSUMMER TEMPERATURES · MEAN ANNUAL RANGES OF TEMPERATURE · THE ANNUAL MIGRATIONS OF THE ISOTHERMS AND OF THE TEMPERATURE BELTS · COMPOSITE TEMPERATURE CURVES · TEMPERATURE TYPES IN THE EASTERN PROVINCE · TEMPERATURE TYPES IN THE GULF PROVINCE · TEMPERATURE TYPES IN THE PLAINS PROVINCE · TEMPERATURE TYPES IN THE PLATEAU PROVINCE · TEMPERATURE TYPES IN THE PACIFIC PROVINCE · THE ADVENT OF SPRING · THE TEMPERATURE GRADIENTS AND THEIR ECONOMIC SIGNIFICANCE · THE OCCURRENCE OF MONTHS AND OF SEASONS WARMER OR COLDER THAN NORMAL · EXTREME LIMITS OF THE MEAN TEMPERATURES OF INDIVIDUAL MONTHS · TRADITIONS REGARDING UNUSUAL SEASONS · RECENT STUDIES OF EXCEPTIONAL SEASONS · DO TEMPERATURES SHOW ANY PERMANENT CHANGE? · HIGHEST AND LOWEST "RECORD" TEMPERATURES · THE AVERAGE LOWEST TEMPERATURE OF THE YEAR · OTHER FACTS CONCERNING ANNUAL AND MONTHLY MAXIMA AND MINIMA · TEMPERATURE CHANGES DURING TWENTY-FOUR-HOUR INTERVALS · THE DIFFERENCES IN TEMPERATURE FROM DAY TO DAY · DOES THE ANNUAL MARCH OF TEMPERATURE SHOW PERSISTENT IRREGULARITIES?

The Larger Temperature Relations. The larger facts regarding temperature are best seen on the world isothermal maps, which show the course of the (sea-level) isotherms over the oceans as well as over the lands.[1] The isotherms show certain systematic deflections as they pass from ocean to ocean across North America. Thus, in the higher latitudes there is a marked poleward deflection in the northeastern Pacific, and a more moderate equatorward deflection in northeastern North America. In middle and lower latitudes, per contra, there is an equatorward deflection as the isotherms approach the con-

[1] See, for example, the *Challenger* charts, reproduced in the *Atlas of Meteorology*, Plates 1, 3; text pages 7, 9.

tinent from the Pacific, a poleward looping as they enter the continent, and then another gentle equatorward trend as they approach the Atlantic. These deflections, similar to but more marked than those found in corresponding latitudes of Eurasia, result in a crowding of the isotherms on the eastern coasts of the northern continents and a spreading apart on the eastern sides of the northern oceans. The opposite sides of the North Atlantic show this contrast at its best. "In western Europe, one may travel a thousand miles northward without finding so great a change of mean annual temperature as would be found in a voyage of half that distance along our eastern coast."[1] These systematic isothermal deflections follow very closely, and are chiefly due to, the general flow of the great ocean currents, as has been seen in Chapter II.

The mean annual isotherms represent approximately the conditions of spring and autumn. Comparing them with those for January and for July, the midwinter and midsummer months, it is seen that in the middle and higher latitudes the mean annual isotherms are a weak reproduction of those of January. In lower latitudes, on the other hand, the systematic deflections of the former resemble those of July. The cold winters of the central and northern interior may thus be said to control the course of the mean annual isotherms over the higher latitudes, and the hot summers of the southern portion of North America leave their mark on the course of the annual isotherms in the lower latitudes.

In comparison with the mean temperatures of the different latitudes, most of North America is too cold in winter (January). A district of abnormally low temperatures (20°–30° F. below the general mean of the latitude) centers over Hudson Bay and the adjacent lands. Another, of abnormally high temperatures (20° F. above the mean of the latitude), appears over the warm waters of the Gulf of Alaska. Lying to leeward of this latter district a considerable strip along the Pacific coast, extending from Alaska to as far south as southern Cali-

[1] W. M. Davis, "Elementary Meteorology," p. 66. See also G. G. Chisholm, "Handbook of Commercial Geography" (new ed., 1922), pp. 26–27.

fornia, is warmer than the means of its latitudes.[1] The isanomalies[2] are less marked in July. North America as a whole is somewhat warmer than the mean temperatures of its latitudes in July. The greatest plus departure (10° or more) occurs over the western interior deserts of Nevada and Arizona. The regions of Hudson Bay and of Labrador and the Pacific coast are too cool. In the mean for the year, North America, with the exception of its west coast, is colder than normal for its latitudes.

Available Temperature Charts. The fundamental isothermal charts are those for the year, the twelve months, and either the four seasons or the two opposite seasons of summer and winter. With the exception of the mean annual chart this whole series has been constructed anew, on a uniform basic period, for the *Atlas of American Agriculture*.[3] These charts show actual temperatures, not reduced to sea level. They super-

[1] C. F. Batchelder, "A New Series of Isanomalous Temperature Charts, Based on Buchan's Isothermal Charts," *Amer. Met. Journ.*, Vol. 10 (1893–1894), pp. 451–474. The charts are reproduced in the *Atlas of Meteorology*, Plate 2; text page 8.

[2] Equal departures from the mean temperature of the latitude.

[3] Several of the charts in the Temperature Section of this *Atlas*, including all the basic ones, were given advance publication in *M. W. R.*, Vol. 49 (1921), Charts XLIX — 165 to 184. The basic charts (for example, the seasonal and monthly mean temperatures, the mean daily maximum, the mean daily minimum, etc.) were not essentially changed by the additional data which accumulated after the originals were prepared and before the final appearance of the *Atlas*. On the other hand, certain of the charts in which extremes were concerned (for example, the highest and the lowest monthly means, the absolute maximum, etc.) needed changing and were therefore revised and brought down to date. As the immediate object of the *Atlas* was to benefit agricultural interests, the needs of that group were primarily in mind in planning the sections on climate. Hence, while all the maps and curves are of importance and will prove useful in a variety of investigations, there is naturally considerable detail which is not of immediate significance in a very general discussion like the present one. Reference is therefore here made to such charts only as have a broad climatic significance. In addition to the basic charts referred to in the present chapter, the *Atlas* also contains charts showing, for each month, the average daily maximum, the average daily minimum, and the highest and lowest monthly means for twenty years (1895–1914); the average dates when the mean daily temperatures rise above or fall below certain critical values; the number of times in twenty years that the lowest temperature was a certain number of degrees or more below the average, and the average number of days with minimum temperature 32° or lower. There are also graphs illustrating, for selected stations, significant temperature characteristics. Figs. 33, 34, 47, 48, and 49 in the present chapter were

sede all other existing isothermal maps of the United States and will for years to come remain the standard set.

Mean Annual Temperatures. Certain broad generalizations regarding the distribution of the mean annual temperatures over the United States are readily made.[1] With a wide range of latitude, with two flanking oceans on the east and west, and with a warm Gulf on the south, it is inevitable that the United States should show considerable differences of temperature between north and south and between the narrow windward west coast and the interior. Roughly, east of the 105th meridian the northern tier of states has 40°–50°, the central tier 50°–60°, and the southern tier over 60°. The Lake Superior region has below 40°, and southern Florida and southeastern Texas over 70°. The east-and-west course of the isotherms is modified by the Appalachian Mountain system, where the lower temperature due to elevation is indicated by the equatorward deflection of the isotherms.

West of the 105th meridian the chart is far from satisfactory owing to the deficiency of observations over the mountains and plateaus. Temperatures over 70° are indicated in southwestern Arizona and southeastern California. Most of the

redrawn from Figs. 12, 42, 6, 3, and 7, respectively, in the *Atlas*. See also R. DeC. Ward, "Bibliographic Notes on the Temperature Charts of the United States," *M. W. R.*, Vol. 49 (1921), pp. 277–280. In addition to the publications here listed, reference may be made to the following publications of the last twenty years which deal with temperature data: W. B. Stockman, "Temperature and Relative Humidity Data," *U. S. Weather Bur. Bull. O*, 1905 (contains tables of maximum and minimum temperatures recorded at Weather Bureau stations in each month from the beginning of observations to the end of December, 1904; also the mean monthly and mean annual maximum and minimum temperatures, and charts showing the absolute maxima and absolute minima); F. H. Bigelow, "The Daily Normal Temperature and the Daily Normal Precipitation in the United States," *U. S. Weather Bur. Bull. R*, 1908 (the daily normals are obtained by a process of smoothing; the monthly means are plotted; a curve is drawn through these twelve points, and the temperatures for each day are then scaled off); idem, "Report on the Temperatures and Vapor Tensions of the United States," *U. S. Weather Bur. Bull. S*, 1909 (the statement on the title page, "reduced to a homogeneous system of twenty-four hourly observations for the 33-year interval 1873–1905," is somewhat misleading. The means are not all reduced to the same period of years. "Homogeneous" refers only to the reduction to true means).

[1] The latest chart of mean annual temperature is that included in the set of *Climatic Charts of the United States* (United States Weather Bureau). This chart is not reproduced here, as the mean annual temperatures are of comparatively little interest over most of the country, owing to the large annual ranges.

northern portion of the Plateau district (north of latitude 38° N., and, in the southeastern part of the district, as far as latitude 35° N.) has 45°–50°. There is a decrease along the Pacific coast from 65° in the south to 50° in the north. Deflections and irregularities due to topography are especially marked over the southwestern interior. A comparison of the temperatures on the Pacific and the Atlantic coasts shows that these do not differ appreciably in middle and lower latitudes. In the north, however, the Pacific coast is distinctly the warmer. Thus, at latitude 45° on the Pacific the mean annual temperature is between 50° and 55°; on the Atlantic it is between 40° and 45°. San Diego in California and Charleston in South Carolina, on the other hand, both in the same latitude, have almost the same mean annual temperatures.

Midwinter Temperatures. The greatest differences in temperature between different parts of the United States occur in winter, and it is then that the contrasts between land and water controls are most marked (Fig. 33). In midwinter (January) the extreme continental effect is seen in the occurrence of mean monthly temperatures of below 10° over the northern interior between the Great Lakes and the Rocky Mountains, and in northernmost Maine. January means below zero are indicated on the northern border of North Dakota and Minnesota. The equatorward deflection of the isotherms over the northern interior region is a striking feature, which emphasizes, among other things, the fact that the western border of the Great Plains and the eastern foothills of the Rocky Mountains are warmer, in spite of their greater elevation, than the lower-lying country farther east. The general tendency of the eastern and southern isotherms to bend in conformity with the Atlantic and Gulf coasts shows a tempering effect of the ocean and Gulf waters, which, however, is not very marked owing to the general prevalence of offshore winds. Along the northern shores of the Gulf of Mexico temperatures of 50°–55° are found. Southern Texas and most of Florida have over 55°. Going south from Duluth to New Orleans, or from the coast of northern Maine to southernmost Florida, the January mean temperatures increase at the rate of about 2.5° for each latitude degree

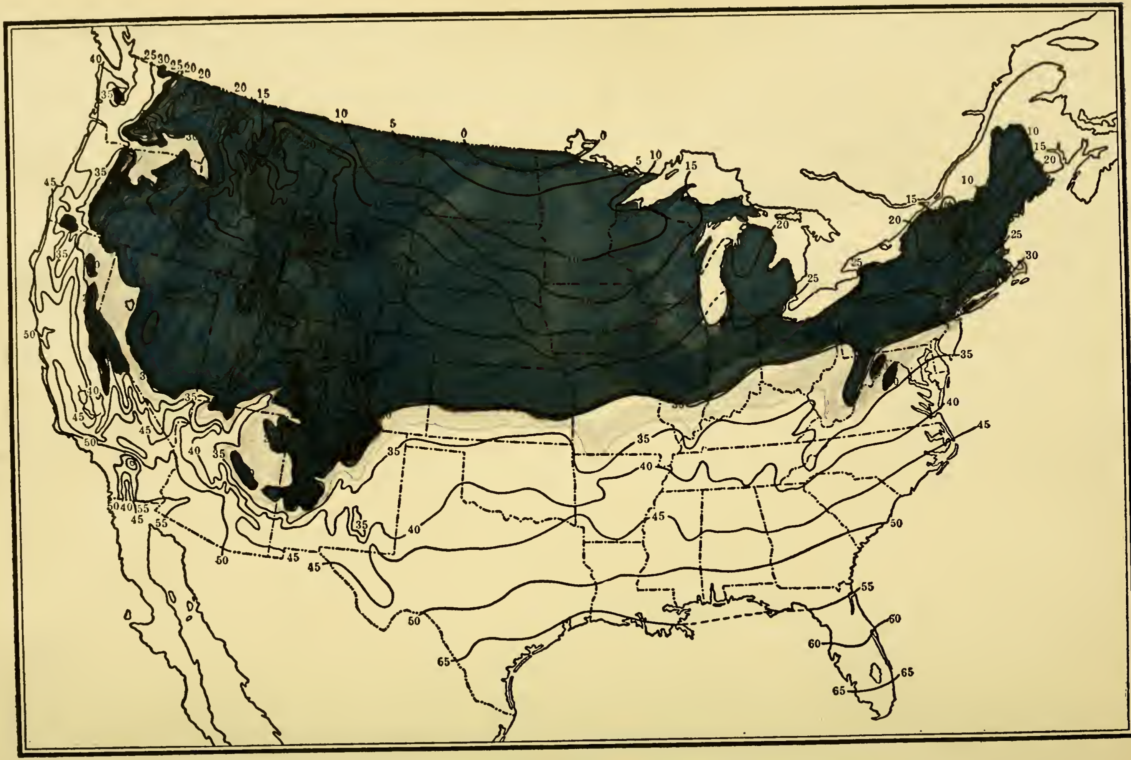

FIG. 33. Average Monthly Temperature for January

(roughly seventy miles). The popularity of Southern winter resorts is thus easily explained. Health-seekers and warmth-seekers find the average monthly temperature in January increasing at the rate of about 1.5° for every hour of travel southward in a fast express train.

There are two or three areas in the eastern United States where marked local irregularities in the isotherms exist. The northern portion of the Hudson-Lake Champlain depression is clearly indicated by the poleward deflection of its isotherms. The central Appalachians show an equatorward warping of the isotherms and the occurrence of low mean temperatures in certain valleys. A third and more notable local irregularity is seen in the lake region. The moderating influence of the open waters is carried to leeward by the prevailing westerly winds, so that certain stations on the lee shores have somewhat higher winter means than do those on the opposite shores. The effect is clearly shown in the case of Lake Michigan, where the isotherms of 20° and 25° are bent poleward over the lake and equatorward again over the lower peninsula of Michigan. The general spreading and warping of all the isotherms in the lake region is another indication of the local effects due to the lake waters. Several writers have called attention to this situation.[1] In one of the most recent of these studies Eshleman has made a comparison of the temperatures at Grand Haven, Michigan, on the eastern shore of Lake Michigan, with those at Milwaukee, Wisconsin, on the opposite shore, and has also compared Grand Haven with a group of inland stations in the same latitude, in Wisconsin, Iowa, and South Dakota. During the colder season the mean monthly temperatures at Grand Haven run 2°–4° higher than those at Milwaukee and 5°–8° higher than those at the group of western inland stations.

Blodget emphasized several of the most striking character-

[1] See, for example, Alexander Winchell, "The Isothermals of the Lake Region," *Proc. Amer. Assoc. Adv. Sci.*, Vol. 19 (1870), pp. 106–117; C. Abbe, "The Influence of the Lakes on Temperature of the Land," *M. W. R.*, Vol. 28 (1900), pp. 343–345; W. F. Cooper, "Air and Water Temperatures," ibid., Vol. 33 (1905), pp. 521–524; C. H. Eshleman, "Climatic Effect of the Great Lakes as Typified at Grand Haven, Michigan," *Meteorological Chart of the Great Lakes*, United States Weather Bureau, September, 1913.

istics of the winter temperature distribution in the United States.[1] He called attention to the occurrence of the lowest winter temperatures to the west of the Great Lakes, "the point of natural minimum" being "broken up by the Lakes" whose location is "most fortunate for the cultivable districts of this part of the United States." He noted the diminished warming effect of the Gulf of Mexico in winter owing to the "great relative refrigeration of the continent, generally, and the consequent prevalence of land (that is, offshore) winds," and called attention to similar conditions along the Atlantic coast, where, "if the prevalent winds were reversed, the climate would be greatly softened."

In the East, in spite of various irregularities in the isothermal system, the major control over the temperature distribution is obviously latitude. The situation is wholly different over the western mountain and plateau area. Here the isotherms are warped and crowded or spread apart as the topography may determine. A study of the map itself is the only way to gain a good view of the actual situation. It is true that latitude plays a considerable part in determining certain large facts. For example, while the southern deserts of Arizona and southeastern California have January mean temperatures over 50°, the northern Plateau, in Washington, has about 20°. But the deserts are of low altitude, whereas parts of the Washington plateau attain elevations of from 1500 to 2000 feet. Beyond these large facts the temperatures of the mountain and plateau area cannot be adequately generalized. Under control of altitude and local topography, supplemented to some extent by latitude, the January isotherms vary from 15° to 55°. Further discussion would lead well into the field of local climatology. It should be observed, however, that the temperatures average higher west of the Rocky Mountains than they do to the east, although the altitudes to the west are greater.

In the Pacific Province a very striking feature is the parallelism of the westernmost isotherms with the coast. From north to south there is only a slight increase in temperature. The stations on the coast of southern California, for example, are

[1] Lorin Blodget, "Climatology of the United States," 1857.

only a very few degrees warmer than San Francisco, and the extreme northern coast of Washington (40°+) is less than 15° cooler than the extreme southern coast of California (50°+). Latitude is obviously here a very subordinate control, especially when the Pacific coast is compared with the Atlantic. The rate of change of temperature along the entire length of the Pacific coast is only about 0.8° per latitude degree, which is less than one third of the temperature gradient along the Atlantic coast in the same month. Clearly the prevalence of onshore winds from a relatively warm ocean explains the moderate and noticeably uniform winter temperatures along this coast. Inland, various topographic features are distinctly indicated in the isothermal system. The California valley, the lower portions of which are inclosed by the 45° isotherm, is contrasted with the lower temperatures of the Sierra Nevada. In southern California the interior highlands are distinctly cooler than the seacoast. The valley of Oregon is outlined by its own inclosing isotherms, as is the Columbia River valley, where the isotherms indicate almost as well as contour lines the gap through the mountains. In Washington the Olympics and the Cascades are notable features, with their lower temperatures as compared with those of the neighboring lower lands. A comparison between the mean January temperatures on the Pacific and Atlantic coasts is interesting. The coast of southern California has essentially the same temperatures as have the corresponding latitudes on the southern Atlantic coast. San Francisco is 10°–15° warmer than the corresponding Atlantic coast. The coast of northern Oregon is 20° warmer than the same latitude on the coast of Maine. The excess in favor of the Pacific coast thus increases to the north.

The economic consequences of such winter temperatures as are experienced in the United States are many and varied. Over the cold northern and eastern sections agricultural operations must largely or wholly cease, and there is a general abandonment of outdoor labor except in the case of certain occupations such as lumbering and ice-cutting that are best, or exclusively, carried on in winter. Artificial ice-manufacturing establishments are located almost altogether in the

central and southern tiers of states and on the Pacific coast; natural ice comes from the North.[1] At one time, in the days of active trade between New England and the East, ice from Wenham Lake, near Salem, Massachusetts, was known even in India. Transportation conditions are to a considerable extent readjusted during the winter. There is difficulty with severe cold and deep snows. The heavy summer vacation travel to the North and East ceases, but is replaced, to an increasing degree, by winter travel to the genial South. The close of navigation on the Great Lakes turns the transportation of freight to the railroads or leads to a delay in shipments till spring. The principal manufacturing belt of the country lies north of the districts where indoor work is considerably interfered with by summer heat, and south of the region which is blocked by heavy snows and where the waterways are frozen in the winter.[2] Many industries show seasonal controls, such as the manufacture of heavy winter clothing, of overshoes, and of rubbers. There is need of heating the cars which are used to carry food that is injured by cold. Even in the case of the shipment of iron ore, for example, since the ore freezes at temperatures somewhat below 32°, precautions must be taken not to have it exposed long at low temperatures. Over the districts of moderate or warm winters, on the other hand, as in the case of the Southern and Pacific coast states, outdoor and farming operations may continue all winter. The cooler months may and usually do bring a change in the character of the outdoor work but not in its essential nature.

Midsummer Temperatures. Very different are the conditions in midsummer (Fig. 34). The distribution of temperature is far more uniform in July than in January. Between the northern tier of states (east of the Rocky Mountains), with mean temperatures of within a few degrees of 70°, and the southern tier and the Gulf states, with temperatures within a few degrees of 80°, the difference is so small that it attracts

[1] See A. P. Brigham, "Commercial Geography" (1911), Fig. 108 (zones of natural and of manufactured ice).

[2] W. M. Booth, "Effect of Climate on Location of Manufacturing Plants," *Sci. Amer. Suppl.*, Vol. 79, No. 2048, April 3, 1915, p. 219.

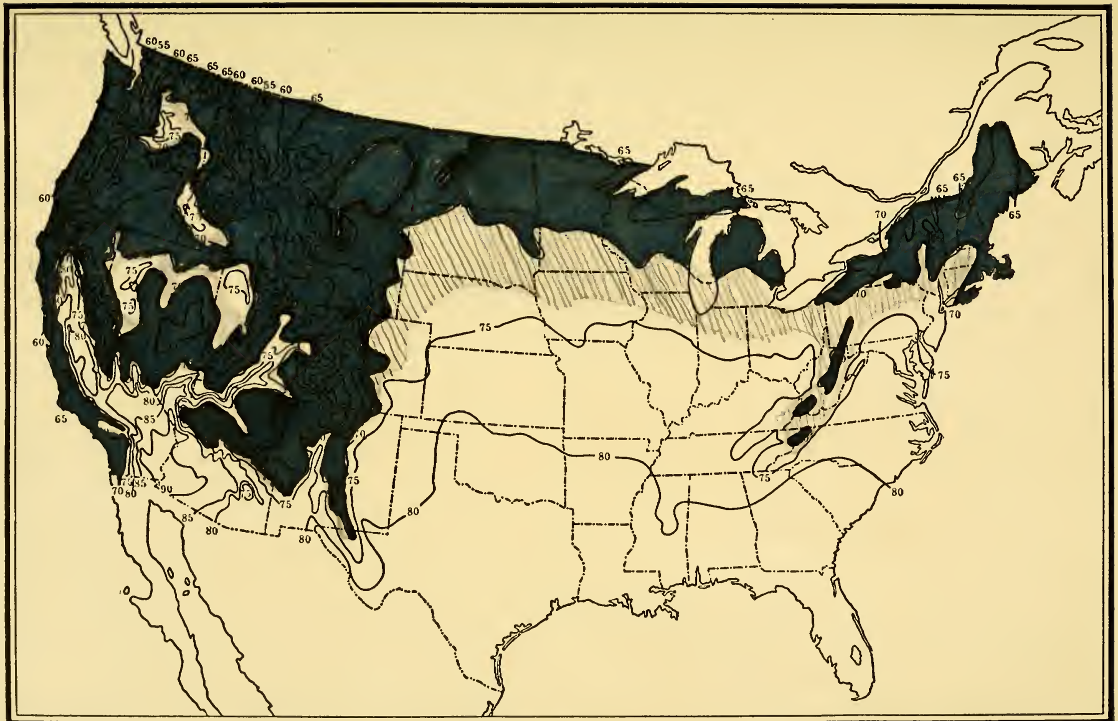

FIG. 34. Average Monthly Temperature for July

attention. On the other hand, the temperature differences between north and south in January are striking because they are so large. In July the rate of change of temperature between New Orleans and Duluth is in round numbers only about 1° F. per latitude degree, while on the Atlantic coast, between Key West, Florida, and Eastport, Maine, it is about 0.8°. So far as the mean temperatures alone are concerned, therefore, a long journey from south to north in search of decidedly cooler summers gives far less change than the corresponding trip from north to south in winter in search of much warmer and balmier climates. Other factors, however, serve to give the northern summer resorts their popularity. Among these are the frequent spells of cool weather, the advantages of cool fresh-water bathing or salt-water bathing, the lower temperatures (due to elevation) found in the mountains of New England and New York, and other conditions. The July isotherms show clearly the cooling effects of the Appalachian Highland in the warping of the lines and in the occurrence of temperatures averaging 5° or even 10° below those of the surrounding lowlands.

The tempering effects of even relatively moderate altitudes are shown in an interesting way by the course of some of the isotherms which are prominent features of the July map in the eastern United States. Take the case of the 70° isotherm, for example. This line follows along the eastern base of the Rocky Mountain system from southern New Mexico northward to northeastern Wyoming, and then makes an abrupt turn eastward across the northern tier of states. Stations at no very great elevations in southern New Mexico are thus seen to have the same mean July temperatures as a long line of places reaching across northern South Dakota, central Minnesota, Wisconsin and Michigan, much of New York, and also southern New England. The situation is somewhat similar, but less marked, in the case of the 75° isotherm. The tempering effects of the Great Lakes may be seen in the warping of the isotherms. Grand Haven, Michigan, has mean temperatures 1° lower than those of Milwaukee, Wisconsin, in July and August, and 3°–4° lower, between April and August, than those of a group of

inland stations on the same latitude west of Lake Michigan.[1] Michigan stations on the immediate lake shore are naturally also cooler than those situated somewhat inland, but this cooling influence on the mean monthly temperatures extends only to a distance of twenty or twenty-five miles inland, according to Henry.[2] Near the Atlantic coast the isotherms "double on themselves abruptly," as Blodget put it, indicating cooling "due either to the southward-flowing cold surface currents or to the upwelling of cold water."[3] The northern coast of Maine has notably cool summers, cooler than those of the eastern coast of Asia in the same latitude.

Over the western Plateau Province the isothermal map is essentially a rough contour map. July mean temperatures below 55° are shown in certain portions of the Rocky Mountains in Montana, Wyoming, Colorado, Utah, and northern New Mexico; also on the Cascades of Washington and Oregon and the Sierra Nevada of California. Much of the Plateau Province has from 65° to 75°. The highest monthly mean (over 90°) occurs over a restricted area of southwestern Arizona and southeastern California. This "heat island" is much smaller and less conspicuous than it appears on earlier charts, as, for example, on the *Challenger* (sea-level) isothermal chart for July, where the 90° isotherm incloses a considerable part of the southern Plateau region. The close crowding of the isotherms on the mountain and plateau slopes; the distinctly lower temperatures at the greater elevations; the contrast between the excessively heated southern deserts and the much cooler, more elevated stations not far away—these are the most striking features in this western interior district. The effects of altitude are here so considerable that latitude and land and water controls are of relatively subordinate importance. Hence the popularity (at least in part) as summer vacation resorts of the mountains of Colorado, of Yellowstone National Park, and of other parts of the Rocky Mountain district.

[1] C. H. Eshleman, loc. cit.

[2] See also H. J. Cox and J. H. Armington, "The Weather and Climate of Chicago" (1914), pp. 37–46, 142–145, on the influence of Lake Michigan on temperatures at Chicago.

[3] *Atlas of Meteorology*, p. 12.

On the Pacific slope (Pacific Province) there are three very striking features on the map. (1) The seaward isotherms closely parallel the coast line, giving, as Blodget remarked, "almost absolutely equal temperatures" along this coast.[1] One may travel from the Strait of Juan de Fuca as far south as San Francisco without any change in the mean monthly temperature, and continue the trip to the southernmost part of the coast without reaching a mean temperature as high as 70°. The temperature gradient between San Diego and the Strait of Juan de Fuca is only 0.7° per latitude degree; that is, one may travel north nearly twelve hundred miles without changing the mean temperature more than about 12°, or 1° to a hundred miles. (2) A second notable feature is the extraordinarily rapid temperature gradient between the immediate seacoast of southern California, with its cool summers resulting from the prevailing onshore winds, and the greatly heated interior desert of southeastern California. The west-east gradient from the coast to the southern portion of the San Joaquin valley is also very rapid. This phenomenon "of the juxtaposition of Scottish and mid-African summer conditions" is almost if not quite unique.[2] The superheating of these interior districts is due to their low latitude, abundant sunshine, dry air, and effective inclosure from the sea. (3) The third feature is the marked contrast between the higher temperatures of the interior valleys and the cooler mountain slopes. This is especially well seen in California, where the Sacramento-San Joaquin valley stands out clearly by reason of its fairly uniform high temperatures. This topographic control is naturally less marked farther north. The summers on the Pacific coast are as a whole several degrees cooler than those on the Atlantic.

Mean Annual Ranges of Temperature. The seasonal contrasts in temperature are conveniently summarized by means of the so-called mean annual ranges, which show the difference between the mean temperatures of the warmest and coldest months.[3] The new isothermal charts for January and July

[1] Loc. cit. [2] *Atlas of Meteorology*, p. 12.

[3] The standard chart of mean annual ranges for the world, based on the *Challenger* sea-level isotherms for January and July, is that of J. L. S. Connolly,

have made it possible, by a comparison of the lines of actual temperatures for these two months, to study for the first time in great detail the ranges in all parts of the United States. The greatest differences between the mean temperatures of January and of July are found over the northern interior region between the Rocky Mountains and the upper Lakes; namely, 55°–60°, and even slightly over 60° in some cases. From this center the ranges decrease in all directions. It is to be observed, however, that the continental characteristics of warm summers and cold winters prevail even to the extreme limits of the land area to the east. The absence of any effective mountain barrier on the west, somewhat inland from the Atlantic coast, and the prevalence of offshore winds explain this condition. Thus, ranges of 40°–50° are found even along the central and northern portions of the coast. The modifying effects of latitude and of the Gulf of Mexico are seen in the somewhat smaller ranges which prevail in the Gulf Province (25°–30° or less). Most of the rest of the Eastern Province has 40°–50°. Over the southern Plains and much of the Plateau Province the ranges run from slightly above 40° to somewhat below it.

The Annual Migrations of the Isotherms and of the Temperature Belts. Too much emphasis upon the conditions in January and in July gives a misleading impression of the actual march of temperature through the year. It is important to have clearly in mind the fact of the continual advance or retreat of the isotherms, not only month by month but week by week, and even day by day. The isothermal chart of any one month is merely a "snapshot" of conditions which are in a constant state of flux. It represents no rigid, fixed, permanent situation. The isothermal charts of the twelve months should, if possible, be studied together, as a continuous and interrelated series.

January and July are the extreme types. They simply show the limits reached during the seasonal migration poleward and equatorward. Each of the other maps is almost as important,

"A New Chart of Equal Annual Ranges of Temperature," *Amer. Met. Journ.*, Vol. 10 (1893–1894), pp. 505–506. This chart is reproduced in the *Atlas of Meteorology*, Plate 2, text page 8; in W. M. Davis's "Elementary Meteorology," Fig. 18; and elsewhere. No more recent chart is available for the United States.

in that it marks another stage of advance or retreat. With the northward advance of the sun the succeeding months of late winter, spring, and early summer show the gradual rise in the temperatures everywhere, the changes being greatest over the northern and interior districts which have the greatest mean annual ranges. The seasonal northward advance of the isotherms is naturally most readily seen over the eastern United States, where the lines of equal temperature are well separated and follow more or less along the latitude circles. Even a cursory glance at the charts for January to June shows the northward movement of isotherms which are over the Gulf states in midwinter and travel northward so far that they leave the United States altogether, moving across the international boundary into Canada. The gradual spreading apart of the eastern isotherms as the season advances is also very obvious. In January twelve isotherms are shown between the northern Plains and the Gulf of Mexico. In July, when the continent is well and very uniformly warmed, there are only three. Over the Plateau districts the general system of the isotherms remains more or less the same, month by month, but the lines are on the whole somewhat more crowded during the warmer months in certain areas, indicating greater differences of temperature between lowlands and uplands in summer than in winter in those localities. The seasonal increase in all the temperatures is readily seen if the figures on the charts are noted. On the immediate Pacific coast the parallelism of isotherms and coast line remains a constant feature on all the maps, and the seasonal changes in the actual temperatures are, as already pointed out, relatively slight.

During the cooling months (August–January) the isothermal system travels equatorward. Lines which in summer extended well north over the United States now travel so far south that they disappear from the map; for example, the 70° and 75° isotherms. In their place isotherms which in July were far north in the Arctic regions, or which did not even appear at sea level at all, gradually move equatorward and appear, one after another, on the charts. Over the western mountains and plateaus and, to a less marked degree, over the eastern Appa-

lachians the advance of the colder season means the gradual descent down the slopes, to lower and lower levels, of isotherms which during the warmer months were either on the upper slopes or even in the free air, far above the tops of the highest mountains. Thus the sun is forever impelling advances and retreats, ascents and descents, of all isotherms on all maps. There is no such thing as a fixed condition of temperature distribution. When this conception is thoroughly in mind, isothermal maps have a new meaning. They are no longer dead and rigid, but are full of movement, suggesting an infinite number of relations between the ever-changing temperatures and all of human life and activity.

January and July have been referred to as everywhere the coldest month and the warmest month. This is true for the vast majority of stations and in the long run. There are, however, a few stations exposed to marine influences on the Pacific coast or on the Great Lakes which have retarded maxima or minima. February may then become the coldest month, and August the warmest month. San Francisco is unique in having September its warmest month, and its October is actually warmer than its July and August. This peculiar condition results from the prevalence of strong onshore winds blowing through the Golden Gate in summer and induced by the excessive heating of the interior valley. The hotter the valley, the more marked are these inflowing cool winds from the Pacific Ocean.

Composite Temperature Curves. Many of the larger facts concerning temperature may be more clearly and more conveniently summarized in a series of curves than by means of the ordinary isothermal charts.

In a broad study of the essential characteristics of temperature over an extended area such as that of the United States, the conventional diagrams showing the annual march of temperature at certain selected stations are not wholly satisfactory. Such curves illustrate conditions which are often representative of small districts only. They not infrequently emphasize somewhat too strongly the local controls and peculiarities at individual places. They inevitably become associated with the

names of the particular stations whose conditions they represent and may thus fail to bring clearly before the mind the larger and more general conditions which characterize broad areas. Therefore, in addition to the temperature curves for individual stations, it is useful to employ *composite* curves showing the annual march of temperature as illustrated by the mean monthly values summarized for a group of stations in the same general region or climatic province. Familiarity with these fundamental curves enables anyone to answer reasonable questions regarding the march of temperature in any part of the United States and also, given the monthly temperatures of an unknown station, to name the climatic province in which that station is situated.[1] The curves are not intended to show the exact temperatures at any station. If it were desired to illustrate local conditions, an almost indefinite number of curves would be needed which, however interesting and important in themselves, would not serve the purpose of a general study. Anyone who seeks such specific and exact information can find it in the very complete tabulations of data in *Bulletin W* and in other publications of the Weather Bureau. In the composites, representative data have been included for each of the more important subdivisions given in *Bulletin W*.

Temperature Types in the Eastern Province. Latitude, not altitude, is the fundamental control of temperature in this province. Hence, for the present purpose, it is both logical and convenient to give three composite curves for this large

[1] These curves are constructed as follows: For each climatic province a representative series of stations is selected, ranging in number from ten to fifteen or twenty. In the majority of cases these are regular Weather Bureau stations, because they have the longest records and show conditions over the districts of densest population. Most of the places selected are fairly near sea level, but in the western mountain and plateau districts several of them are five thousand or more feet in elevation. In addition, the data for certain coöperative stations with long records are included in order that the temperature in localities where there are no regular Weather Bureau stations may have representation. Altitudes above those of considerable human settlement are, however, not taken into account. More coöperative observers' records are used in the West than in the East. The data have not been reduced to a uniform basic period. Such reduction is unnecessary when observations for several stations, at various altitudes, and with diverse topographic environment, are included in one general summary. Curves showing the annual march of temperature at selected stations are given in Fig. 1 of the Temperature section of the *Atlas of American Agriculture*.

area, each curve representing an east-west belt of about 5° of latitude in width. The first of these (Fig. 35) is for the northern tier, north of latitude 45° N., which extends from eastern North Dakota (including northeastern South Dakota) eastward across Minnesota and then across the northern portions of Wisconsin, Michigan, and New England. The second (Fig. 36) is for the central tier of states, between latitudes 40° and 45°, lying between the eastern margin of the Great Plains and the Atlantic. The third (Fig. 37) is for the belt between latitude 40° on the north and the Gulf Province on the south, and extends from the Great Plains to the Atlantic. This may be called the southern tier.

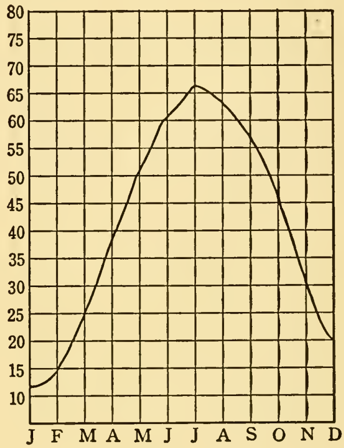

Fig. 35. Temperature Type, Eastern Province, Northern Tier
Mean annual, 40°±; range, 55°±

Figs. 35, 36, and 37 may best be considered together. The mean annual temperatures and the mean annual ranges are given in round numbers below the curves. All three curves are distinctly continental in character. January and July are the coldest and warmest months respectively, and the annual ranges are large. From north to south the (composite) mean annual temperatures increase from about 40° to slightly below 60°, which is at the rate of about 10° for 5° of latitude, and the mean annual ranges decrease from about 55° to slightly over 40°. The increasing mildness of the winters and the increasing heat of the summers from north to south also appear distinctly in the differences in the position of the three curves on the coördinate base. From the fact that each of the three tiers covers a range of about 5°, it follows that the northern stations will have colder winters and lower mean annual temperatures than the stations in more southern latitudes in the same tier. Thus the January means at the northernmost stations are in some cases as much as 10° (more or less) lower than those shown in the curves, and the

southernmost January means are higher than those of the curves by the same amount or less.[1] Among the special characteristics which distinguish the temperature curves in different portions of the Eastern Province the following may be noted. It is a rather striking fact that the temperature conditions between the middle or even the western portions of the individual belts do not differ very greatly from those in the east, in spite of the considerable longitudinal extent of the belts. The reason, as previously stated, is found in the fact that, chiefly under the control of the prevailing winds, the continental climate of the interior reaches the Atlantic Ocean. It is true, as has been pointed out, that the winters of the northernmost interior are colder than those farther south in the same belt; but if we take a belt of country like that between Chicago and Boston, for example, which the writer for convenience describes as the "New York Central belt," it is found that the mean annual and the mean monthly temperatures are essentially the same all along this belt. Another special modification of the composite curves shown in Figs. 35 and 36 appears around the Great Lakes, where "marine" influences at certain stations result in somewhat tempered winters and in a retarded minimum, February being either slightly colder than January, or the two months having nearly the same mean temperature. A third modification, of a more local type, is seen in the cooling influence of the Atlantic Ocean at certain coast stations during midsummer. The coast of Maine is especially favored in this respect. Again, the modifying influence of altitude may be seen in the annual march of temperature at many stations

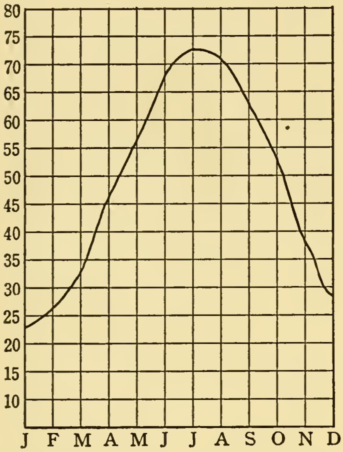

FIG. 36. Temperature Type, Eastern Province, Central Tier
Mean annual, 50°—; range, 50°—

[1] "Northernmost" and "southernmost" refer to the most northern and most southern of the group of stations selected to make up the composite curve.

scattered throughout the Appalachian area, from New England far to the southward.

Temperature Types in the Gulf Province. Fig. 38, which gives the composite curve for the Gulf Province, should be taken as part of the sequence already discussed in the preceding paragraphs. The Gulf Province is obviously only a fourth—the southernmost—tier of the Eastern Province taken as a whole. From north to south the mean annual temperatures of these four belts are seen to increase about 10° from one tier to the next. The Gulf Province thus has a composite mean annual of slightly below 70°. Its range is also about 10° less than that shown in Fig. 37. The increasing mildness of the southern winters (individual January means are slightly over or under 50°) and the somewhat higher summer temperatures (July and August means are usually within a degree or so of 80°) are characteristic features. It will also be noted that August differs less from July than is the case in the preceding composites. The prevalence of onshore winds along the southern coast during the summer months, together with the resulting partial marine control, doubtless explains this condition.

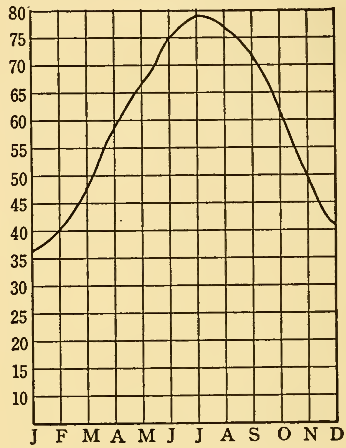

Fig. 37. Temperature Type, Eastern Province, Southern Tier
Mean annual, 60°—; range, 40°+

Temperature Types in the Plains Province. The climate of the Great Plains differs from that of the eastern United States in rainfall rather than in temperature. The temperatures are here illustrated by two composite curves, one for the northern Plains and one for the southern Plains. The line of division between the two roughly follows latitude 40°. Fig. 39 shows the conditions based upon the data for a number of stations in Montana, eastern Wyoming, and the western portions of North and South Dakota and of Nebraska.

Fig. 39 is very similar to Fig. 35, but has slightly warmer summers, the composite mean annual range, expressed in round numbers, being about the same. At the northern Plains stations, however (for example, in North Dakota), the ranges are larger (over 60°), and the January means are 10° or so lower than those of the composite. At other stations, especially those farther south, the midwinter means are 5° or so above the composite means. There is also a variation of 5°–10° in the mean annual temperatures according to the location of the individual stations. The rapid rise of temperature in spring, the fairly close similarity of the July and August means, and the rapid fall after the heat of the summer is over are noticeable. The warm summers of this great interior region of cold winters are an important climatic asset in relation to crop growth.

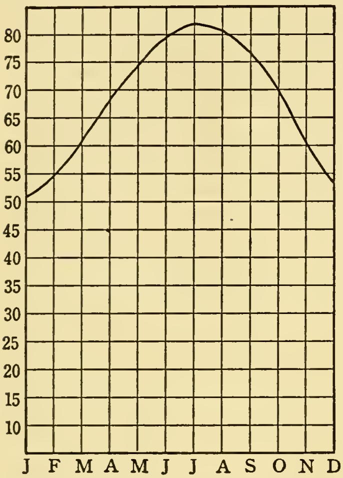

FIG. 38. Temperature Type, Gulf Province

Mean annual, 70°–; range, 30°±

The southern Plains (Fig. 40) have higher mean annual temperatures (55°–60° as against 45°–), smaller ranges (40°+ as against 55°–), much milder winters (warmer by about 15°–20° on the average in January), and somewhat warmer summers (July mean about 10° higher) than the northern Plains. Comparing Fig. 40 with Fig. 38 it is seen that the latter has warmer winters, slightly warmer summers, and a smaller mean annual range. There is, however, naturally a very close correspondence between the Southern Plains Province (Fig. 40) and the southern tier of the Eastern Province (Fig. 37). The effect of latitude within the limits of the Southern Plains Province is shown in the colder winters and lower mean annual temperatures at the northern stations. In the south, July means of 80° and slightly more occur.

Temperature Types in the Plateau Province. The curves for the northern and southern portions of the Plateau Province are necessarily based upon data from stations differing greatly in their topographic environment and altitude. Individual localities therefore show considerable departures from the general means shown in these diagrams. Into the details of such variations the present discussion cannot attempt to go. If

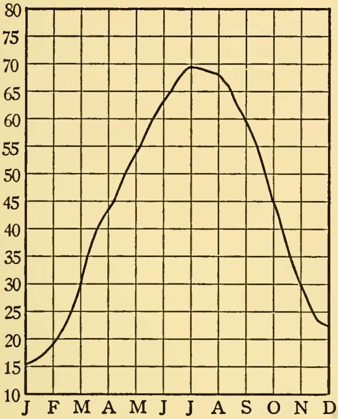

Fig. 39. Temperature Type, Northern Plains Province

Mean annual, 45°—; range, 55°—

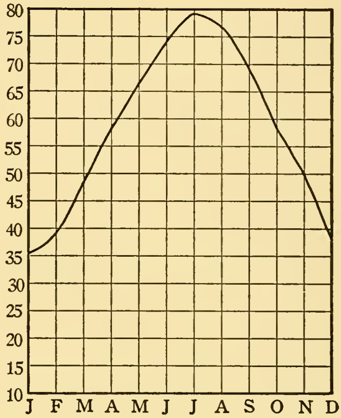

Fig. 40. Temperature Type, Southern Plains Province

Mean annual, 55°–60°; range, 40°+

a very rough generalization is desired it may be stated that there may be a variation of 5°, plus or minus, in the annual, January, and July means from those shown in the composite. A comparison of Fig. 41 with Fig. 39 shows that the latter district, east of the Rocky Mountain barrier, has colder winters, lower mean annuals, and larger ranges, whereas the summers are practically the same. The central tier of the Eastern Province (Fig. 36) has a very similar curve to that of Fig. 41, but the latter has milder winters and a smaller range.

The Southern Plateau Province includes so great a range of latitude (nearly 10°) and so varied a topography that a single composite curve is of little significance. The more northern and the higher stations differ greatly from those on the low-

lying deserts to the south in the summer "heat island" of this interior region. The data used in the construction of Fig. 42 do not include the latter group of stations. It is at once seen that Figs. 41 and 42 are practically identical, as is to be expected when Fig. 42 includes only such stations as are in the northern portion of the southern Plateau and at considerable altitudes. This general fact is worth bringing out. There are

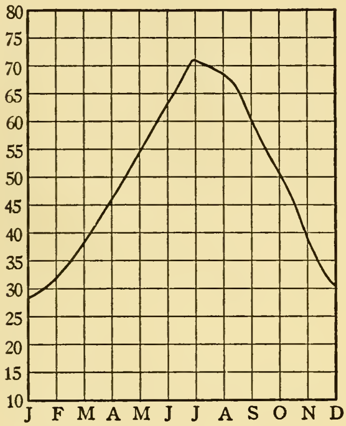

FIG. 41. Temperature Type, Northern Plateau Province

Mean annual, 50°±; range, 40°+

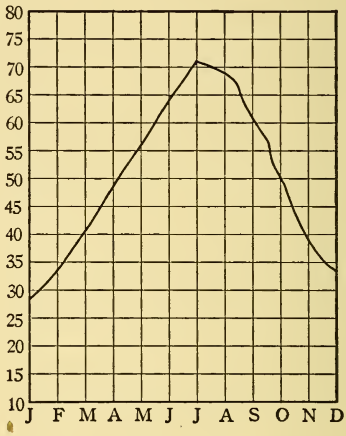

FIG. 42. Temperature Type, Southern Plateau Province

Mean annual, 50°±; range, 40°+

stations over the Plateau whose mean annual temperatures and mean monthly temperatures are very similar to those of stations in the central tier of the Eastern Province, but the other climatic characteristics are quite different.

Stations in the low-lying and arid "heat island" of southern Arizona have quite a different temperature curve from the composite of Fig. 42. Fig. 43 is based on the data for certain well-known and representative stations in southern Arizona. In this diagram the scale is the same as in the other figures, but the position of the individual temperature readings on the coördinate paper has been changed in order to accommodate the higher summer means. The winters on the southern "deserts" are decidedly milder and the summers hotter

than is the case at the stations situated in the north and on the elevated plateaus. Thus the mean annual temperatures at the southern localities are about 70°, and the July means reach and even slightly exceed 90°. There is little likelihood of confusing the temperatures in southern Arizona with those of the Gulf Province (Fig. 38). The former has distinctly hotter summers, although the annual means are more or less the same.

Temperature Types in the Pacific Province. For the purpose of the present discussion the Pacific slope is conveniently subdivided into Northern Pacific Province and Southern Pacific Province, and the latter into (1) coast and (2) interior valley. Many other local peculiarities of temperature distribution would appear if further subdivision were attempted, but the resulting increase in the number of composite curves would offset the object in mind.

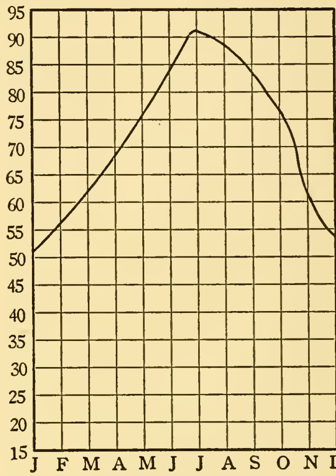

FIG. 43. Temperature Type, Southern Plateau Province (the Southern Desert Lowlands)

Mean annual, 70°+; range, 40°—

The curve for the Northern Pacific Province (Fig. 44) is based upon data for the coast, the Puget Sound region, and the interior valleys. In the north the temperatures in the longitudinal valleys do not differ as much from those of the coast and of the Sound as do those of the Sacramento-San Joaquin valley, farther south, from the temperatures of the southern coast stations. Hence it does not seem necessary in a very general consideration such as that in hand to make more than one curve for the Northern Pacific climatic province. The summers of the interior valleys, especially in southern portions of Oregon, are, however, naturally warmer by several degrees than those of stations like Seattle or Tacoma. The composite curve (Fig. 44) at once shows the marine influence on a windward coast. The winters are milder than those shown on any of the pre-

ceding curves except in the Gulf Province (Fig. 38) and on the desert lowlands of southern Arizona (Fig. 43), but are not unlike those of the southern tier of the Eastern Province (Fig. 37) and of the southern Plains (Fig. 40) so far as the mean temperatures alone are concerned. The summers average cooler than those in any of the preceding curves, even than those of the northern tier of states in the Eastern Province (Fig. 35). The range (about 25° only) clearly indicates the equability of the Pacific slope climates. The departures, at individual stations, of the annual and of the January means from those shown on the curve are too small to call for comment. The July means differ by roughly about +5° (in the southern interior valley of Oregon) to about −5° (on the extreme northwestern coast).

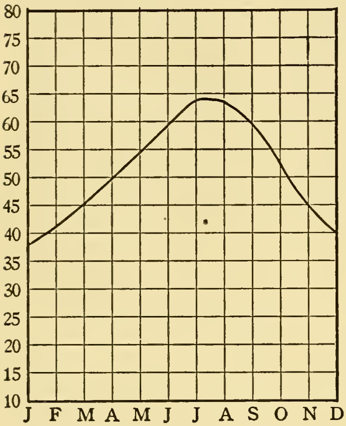

Fig. 44. Temperature Type, Northern Pacific Province

Mean annual, 50°+; range, 25°±

A composite of the southern Pacific coast conditions is given in Fig. 45. The stations included in the composite are nearly all south of San Francisco. Here are the most equable temperatures shown in any of the curves. The range is only about 15°, and the monthly means are all included between 50° and 65°. The retardation of the maximum into August is seen at several of the coast stations, although not at all, and is sufficiently frequent to appear on the composite. This is distinctly a marine characteristic. On the extreme northern coast of California the mean annual temperature is a few degrees lower than that of the composite curve, and on the extreme southern coast it is about the same amount above the general mean.

Fig. 46 is based on the data from about a dozen stations in the Sacramento-San Joaquin valley. It is not unlike that for the Gulf Province (Fig. 38), but the mean annual temperature is higher, and the range is smaller in the latter. The July

means in the California valley are higher than those seen in any other curve except that for the Gulf (Fig. 38) and that for the "heat island" (Fig. 43), but are only slightly above those of the southern tier of the Eastern Province (Fig. 37). A natural comparison is that between the coast and the interior of California (Figs. 45 and 46). The continental controls in the latter are obvious. In the interior July is the warmest month, as contrasted with the (frequently) retarded maximum in August on the coast. The winters are milder on the coast, and the summers decidedly cooler. Hence the mean annual range in Fig. 46 is decidedly greater (by about 20°) than that in Fig. 45. The northern Pacific coast winters (Fig. 44) are not quite so mild as those of the California valley, as is to be expected from the higher latitudes and other controls in the former case; but the summers of the northern Pacific are decidedly cooler than those of the southern interior valleys. In spite of the great extent of the California valley in a north-south line, the temperatures are remarkably uniform throughout the district. The maximum departures from the composite means are somewhat less than +5° at the southern stations in July. The foothills of the Sierra Nevada have their own type of temperature curve, their cooler summers, as compared with those on the valley floor, being a valuable asset in the popularity of that district for summer outings.

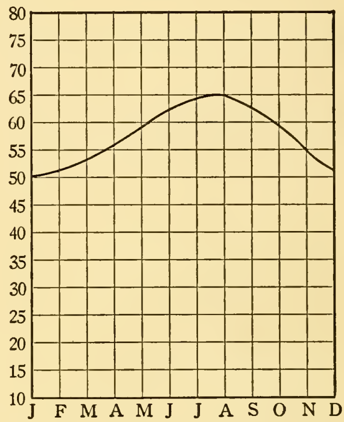

FIG. 45. Temperature Type, Southern Pacific Province (Coast)

Mean annual, 55°–60°; range, 15°

The Advent of Spring. The so-called "advent of spring" may be said to occur when the physiological life of trees and plants awakens after the quiescent stage of the colder months. The temperature of 42.8° F. (6° C.) being about that at which the life of the plant cells begins to stir, a chart showing the position of the isotherm of 43.8° (1° above 42.8°) at the be-

ginning of February, March, April, and May has been taken as indicating the dates of the advent of spring in different sections of the country. Such a chart, proposed thirty years ago by Harrington, shows that spring really comes from the southward and westward; that is, it advances northward and eastward.[1] The progress is not a steady one, but occurs as a series of advancing and retreating fluctuations associated with the occurrence of warm and cold waves, "each advance of warmer weather penetrating a little farther into the cold interior and each successive chilling halting a little north of the southern limit of its predecessor, until finally . . . summer conditions are firmly established."[2] It has been pointed out by Henry that the statement concerning the advance of spring from south and west is really strictly applicable only to the northern portions of the Missouri, Mississippi, and Ohio valleys.[3] On the Pacific coast plant activity to a greater or less degree continues through the colder months, and over the rough and broken topography of the Rocky Mountain and Plateau districts frequent local spring frosts, following warm days, interfere with the orderly advance of spring.

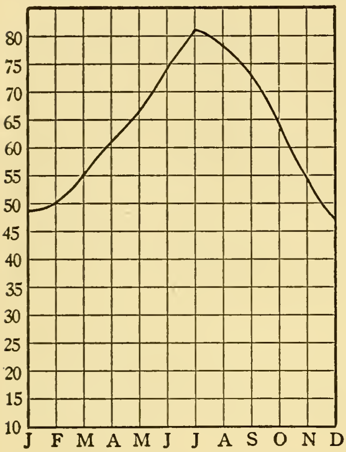

FIG. 46. Temperature Type, Southern Pacific Province (Interior)

Mean annual, 60°–65°; range, 35°±

In connection with this same general matter A. D. Hopkins, of the United States Bureau of Entomology, has made an extended investigation of the times of budding and development of wild plants and trees, as well as of the dates of crop planting. From these data the rate of northward, eastward, and upward progress of life activity in spring has been worked out. It ap-

[1] M. W. Harrington, "The Advent of Spring," *Harper's Magazine*, Vol. 88 (1894), pp. 874–879.

[2] A. J. Henry, "Climatology of the United States," p. 21. [3] Loc. cit.

pears that in temperate North America as a whole there is in spring and early summer an average northward and eastward advance of 1° of latitude (about seventy miles) in four days and an upward advance of four hundred feet of altitude in the same time. The reverse movements take place in late summer and in autumn. This "bioclimatic law" of latitude, longitude, and altitude naturally varies under many local controls, such as topography, rainfall, exposure, soil, etc.[1]

The Temperature Gradients and their Economic Significance. With the warm Gulf of Mexico in the south and the cold continent to the north, the January isotherms over the eastern United States must necessarily be closely crowded, as already pointed out. The rapid January poleward temperature gradient on the Atlantic coast from southern Florida to northern Maine (about 2.5° per latitude degree), already referred to, remains essentially the same if Labrador be taken as the north end of the scale instead of Maine. Considering the distance, this is the steepest temperature gradient in the world. Where such rapid temperature gradients occur elsewhere they are limited to much shorter distances, as, for example, in the case of the opposite sides of mountain ranges. It is a noteworthy fact that in the United States there are no transverse mountains to help in the production of this remarkable contrast between north and south. Woeikof first called attention to the economic importance of this steep temperature gradient.[2] The products of tropical and of polar lands are here separated by less distance than is the case anywhere else in the world. At the same time communication between these districts of sharply contrasted climates and types of vegetation is easy. Labrador is an Arctic land, where man's food must be sought chiefly in the

[1] A. D. Hopkins, "Periodical Events and Natural Law as Guides to Agricultural Research and Practice," *M. W. R. Suppl. No. 9*, 1918. See also, by the same author, "The Bioclimatic Law as Applied to Entomological Research and Practise," *Sci. Monthly*, Vol. 8 (1919), pp. 496–513; "The Bioclimatic Law," *Journ. Wash. Acad. Sci.*, Vol. 10 (1920), pp. 34–40; "Modifying Factors in Effective Temperature; or A Principle of Modified Thermal Influence on Organisms," *M. W. R.*, Vol. 48 (1920), pp. 214–215; "Bioclimatic Zones Determined by Meteorological Data," ibid., Vol. 49 (1921), pp. 299–300. See also G. A. Pearson, "Temperature Summations with Reference to Plant Life," ibid., Vol. 52 (1924), pp. 218–220.

[2] A. Woeikof, "Die Klimate der Erde" (1887), pp. 43–44.

ocean. Florida, on the other hand, is in many respects tropical. This idea has been somewhat expanded by Miss E. C. Semple:[1]

> This approximation of contrasted climatic districts in North America was an immense force in stimulating the early economic development of the Thirteen Colonies, and in maturing them to the point of political autonomy. It gave New England commerce command of a near-by tropical trade in the West Indies, of subtropical products in the southern colonies in close proximity to all the contrasted products of a cold climate—dense forests for naval stores and lumber, and an inexhaustible supply of fish from polar currents, which met a strong demand in Europe and in the Antilles. The sudden southward drop of the 0° C. annual isothermal line toward the St. Lawrence and the Great Lakes brought the northwestern fur trade to the back gate of New York, where it opened on the Mohawk and upper Hudson, and brought prosperity to the young colony.

A steep poleward temperature gradient is a perfectly normal condition on the east coast of continents in middle latitudes as a result of the prevailing winds and the system of ocean currents. Nevertheless it is significant that the January poleward gradient in eastern North America is nearly twice as great as that in eastern Asia (about 1.5°). The explanation was given by Woeikof. North America has a warm body of water—the Gulf of Mexico—on the south. There is also an increasing prevalence of warm (southwest) winds toward the southern portion of the Atlantic coast district, while cold northwesterly winds distinctly predominate in the north. In eastern Asia, on the other hand, cold offshore winds prevail as far south as the tropic, and a cold land occupies the position of the Gulf of Mexico. North of latitude 50° N. the mean annual temperatures in eastern Asia and eastern North America are more or less alike. Farther south, eastern Asia becomes distinctly colder, especially in winter. As Hann put it:[2]

> Comparing eastern Asia with eastern North America, the latter is not too cold in the north but too warm in the south. It is to this fact that the more rapid change of temperature with latitude in

[1] Ellen C. Semple, "Influences of Geographical Environment" (1911), p. 618. See also idem, "American History and its Geographic Conditions" (2d ed., 1913).
[2] J. Hann, "Handbuch der Klimatologie" (3d ed. 1911), Vol. 3, pp. 354–356.

North America is due. The winters on the east coast of Asia are more severe than those on the American coast. Even the interior of America is much warmer than the east coast of Asia in corresponding latitudes.

A comparison between eastern North America and the west coasts of Europe and of northern Africa was apparently first clearly made by Humboldt, who pointed out that the mean annual temperatures found in the higher latitudes (55°–70° N.) on the European side of the Atlantic occur 10°–12° of latitude farther south in North America. In middle latitudes (about 45° N.) this difference decreases to about 4°–5° of latitude. At latitude 30° N. the difference between the two sides of the Atlantic disappears. The January poleward temperature gradient on the west coast of Europe is slightly less than 1° F. per latitude degree, as against a little more than 2.5° F. in eastern North America. The January gradient along the whole Pacific coast of North America as far as Sitka, Alaska, is essentially like that of Europe, and is thus only slightly over one third of that along the whole Atlantic coast. The July gradients on the west coast of Europe (0.65°) and the east coast of Asia (1°) may be compared with those on the Atlantic coast of North America (about 1°) and the Pacific coast of North America (about 0.7°).

The Occurrence of Months and of Seasons Warmer or Colder than Normal. It is a widespread popular belief that individual months in different years are often much warmer or colder than the normal for those months. The expression is a familiar one, "This February was the coldest that I ever experienced," or "September was the hottest that I remember." This belief is usually not based on the fact that the mean temperature of the month in question may have been a degree or so higher or lower than the normal for that month, but rather on the values of the highest and lowest temperatures and on the way in which these were distributed; that is, on the "spells" of heat or cold, and on their severity. In fact, it frequently happens that people think that a month was colder than normal when its mean temperature was actually somewhat above the normal, and vice versa. In other words, the departure of the mean monthly

temperature from the normal cannot in most cases be estimated by the general impression of heat or cold which the month made.

It is a fact that over much of the United States the mean temperature of the same month in different years does depart, often by a considerable amount, from the general mean temperature of that month as derived from the whole series of observations. Almost any random publication which includes the monthly mean temperatures for a series of years, or which gives for any single year the departures of the mean monthly temperatures in that year from the normal, will furnish illustrations of this point. It is, for example, no uncommon thing in any individual year to have December or February colder than January, although in the run of the years January is the coldest month. When the averages of the departures from this general mean are determined (regardless of whether they are + or −), the *mean departures of the monthly means* from their average values are obtained.[1] The calculation of such data is laborious and has not been carried out to any considerable extent. The available results are, however, sufficient to warrant broad generalizations. Supan and Hann determined mean departures of the monthly means for certain parts of North America.[2] Henry has given the most recent tabulation, for a few stations only, from which it appears that the January departures are of the order of 6°–7° on the northern Plains. From this region of maximum average departures there is a decrease to the west, south, and east. The departures for January on the Pacific coast are of the order of 2° to about 2.5°; over the southern Plateau, the southern Plains, and the Gulf states, about 3°; in the lake region, New England, and the central tier of states east of the Rocky Mountains generally, 3°–4°. In July all these departures are reduced to one half or less than one half.[3] The mean temperatures of winter months in the

[1] Also known as the variability of the monthly mean temperatures.

[2] J. Hann, "Handbuch der Klimatologie" (3d ed.), Vol. 1, p. 26; "Lehrbuch der Meteorologie" (3d ed., 1915), p. 110; A. Supan, "Grundzüge der Physischen Erdkunde" (3d ed., 1903), pp. 101–102.

[3] A. J. Henry, "The Climatology of the United States," pp. 31–32. See also idem, "A Warm Winter Followed by a Warm Summer," *M. W. R.*, Vol. 49 (1921), pp. 387–390.

interior of North America are as a whole subject to greater fluctuations than is the case in northern Germany, and almost twice as great as those in England.

While such variations in the mean temperatures of the individual months in different years are significant, they are of slight physiological interest. These differences come a year apart. The monthly means, as has been stated above, are usually not values which can be determined by one's sensations. Furthermore, within a year many other fluctuations of temperature occur, much closer together and of much greater amount, which are directly observable and have many obvious physiological and economic effects.

Extreme Limits of the Mean Temperatures of Individual Months. People are also naturally interested in knowing what mean temperature the coldest January or the warmest February, etc., on record actually had. When such data are available a chart may be drawn showing just what difference there has been, within the period of record, between the mean temperatures of any given month. Such charts have been constructed by Henry and were published in 1906.[1] They show what is known as the absolute range of the monthly mean temperatures for the period included in the observations. Over a large portion of the central United States, including nearly all the Missouri and the middle and upper Mississippi valleys, the mean monthly temperatures of January have differed by 25° and more. To illustrate, a station whose January mean temperature is 10° may have had one January with a mean of 25° and one with a mean of 0° or even slightly below. Such departures having occurred during a relatively short period of observation are of course likely to occur again, and even to be exceeded. From the interior district of the largest ranges there is a decrease in all directions. Over the Atlantic and Gulf coasts the oscillation of the monthly means is roughly 15°–20°; on the Pacific coast and in the southwestern interior it is smaller (8°–16°). In July the amount of such oscillations is about one half of those of January. The California coast has essentially the same conditions in the two months.

[1] A. J. Henry, "Climatology of the United States," Charts XVII, XVIII.

During the period 1895–1914, as shown by the records of about two hundred regular Weather Bureau stations, the *lowest* January monthly mean temperatures ran about 5°–10° below the January means, the departures being smallest on the Pacific coast and in Florida. In July, as is to be expected, the departures are smaller, being about 5° or less.[1]

Traditions regarding Unusual Seasons. As far back as tradition and the non-instrumental record of white men in the United States extend there are references to the occurrences of "unusually" severe or mild winters and of "unusually" hot or cool summers. There were winters in northern sections when there was little ice; when flowers blossomed outdoors; when the ground was hardly frozen. There were also winters when the intense cold lasted almost without interruption; when snows were deep; when outdoor occupations and transportation were greatly interrupted. In the records of the Roxbury (Massachusetts) Church, kept by the Reverend John Eliot, the Apostle to the Indians, the winter of 1646–1647 is described as having brought "no snow all winter long, nor sharp weather," so that it was possible to "go preach to the Indians all this winter, praised be the Lord." Similarly, there are accounts of "unusually" hot and of "unusually" cool summers. The summer of 1816 was a "record-breaking" one. Chauncey Jerome, who was then living in Bristol, Connecticut, wrote:[2]

I well remember on the seventh of June, while on my way to work, about a mile from home, dressed throughout with thick woolen clothes and an overcoat on, my hands got so cold that I was obliged to lay down my tools and put on a pair of mittens which I had in my pocket. It snowed about an hour that day. . . . On the fourth of July I saw several men pitching quoits in the middle of the day with their overcoats on. . . . A body could not feel very patriotic in such weather.

[1] Temperature section of the *Atlas of American Agriculture.*

[2] "History of the American Clock Business for the Past 60 Years, and Life of Chauncey Jerome, written by Himself" (1860), pp. 31–32. Numerous accounts of unusual seasons in New England will be found in Sidney Perley's "Historic Storms of New England," Salem, Massachusetts, 1891. See also W. I. Milham, "The Year 1916—The Causes of Abnormalities," *M. W. R.*, Vol. 52 (1924), pp. 563–570.

Recent Studies of Exceptional Seasons. It is, however, only very recently that any detailed studies of the actual temperature conditions of such abnormal seasons have been made. To take a recent example, the winter of 1917–1918 was remarkably cold, with heavy snowfalls over an enormous area east of the Rocky Mountains. The autumn months were in many cases the coldest on record. December and January "defied the memories of the oldest inhabitants." New minimum temperatures were registered far and wide. Heavy snows with intense cold brought serious economic and transportation disturbances over northeastern districts. Even in the South the truck gardens and fruit crops were seriously damaged. On January 12, 1918, a blizzard, with snow driven by a gale and at a temperature as low as $-20°$, resulted in an almost complete interruption of traffic during two days.[1]

The winter of 1920–1921, on the other hand, was one of unusual and persistent mildness east of the Rocky Mountains. Kincer has given a graphic description of the "involuntary climatic travels" made by the inhabitants of different portions of the eastern United States. The high temperatures were the equivalent of travel over considerable distances to the south.[2] "The people in central North Dakota, climatically speaking, spent the winter near the South Dakota-Nebraska boundary line; those at Sioux City, Iowa, at Kansas City, Missouri; southern Indiana, in northern Tennessee; and Washington, D. C., in southern Virginia." In 1919–1920, a colder winter than usual, "Richmond (Virginia) came north, climatically, to Washington to spend that winter, and went south to Raleigh, North Carolina," in 1920–1921.

In several cases a study of the records has shown that there is often for a time a certain sequence in the occurrence of especially cold or warm or rainy or dry seasons. Facts of this sort have here and there been made use of in making very

[1] An interesting account of this remarkable winter has been written by C. F. Brooks, "The Old-Fashioned Winter of 1917–1918," *Geogr. Rev.*, Vol. 5 (1918), pp. 405–414. See also P. C. Day, "The Cold Winter of 1917–1918," *M. W. R.*, Vol. 46 (1918), pp. 570–580.

[2] J. B. Kincer, "Our Involuntary Climatic Travels (with Special Reference to the Warm Winter of 1920–1921)," *M. W. R.*, Vol. 49 (1921), pp. 18–20.

generalized long-range forecasts. Brooks has discussed the sequence of mild and severe winters in the northeastern United States.[1] An examination of the mean winter temperatures since 1812 shows apparently no other than a chance relationship four fifths of the time. The other fifth includes two notable series of "alternating cold and warm winters, with almost identical preliminaries of a few moderately mild winters, an ordinary or moderately cold winter, and then a severe winter, which opens the alternating series—severe, warm, severe, warm, etc."

The sequence of seasons is apparently not merely chance. The fact seems to have been established that a season appreciably warmer or cooler than normal is a little more likely to be followed by a season, or even by more than one season, with temperature departures in the same direction rather than in the opposite one. The sequence from year to year is less clear.

Examination of fifty to over one hundred years' record at several places in the northeastern United States, for example, Chicago, Cincinnati, Washington, New York, New Haven, and New Bedford, seems to show that alternations between warm and cold winters, when they occur, are mainly what would be expected from chance combinations, although a unique series of twelve unbroken alternations of warm, cold, warm, cold, etc., winters in the seventies and eighties seems to indicate some sort of systematic relationship. In 1916–1922 a very similar series of alternations seemed to be starting, but, as is usual with the duration of periodic weather relationships, this was hardly discovered before it stopped.[2]

It has not yet been possible to work out in detail the actual causes of these marked monthly and seasonal variations in temperature in different years. The explanation, in the United States as elsewhere, undoubtedly lies in the general distribution of pressure over the continents and oceans, that is, in the development and location of the centers of action and in the resulting effects upon the numbers, intensity, and paths of

[1] C. F. Brooks, "Sequence of Winters in the Northeastern United States," *M.W.R.*, Vol. 49 (1921), pp. 71–73.

[2] C. F. Brooks, *Science Service Bull.*

cyclones and anticyclones. It is as yet too early to say in just what ways the variations in the intensity of solar radiation may act to bring about these results.[1]

Do Temperatures show any Permanent Change? While monthly and seasonal mean temperatures are, as has been seen, subject to wide fluctuations, there is no unimpeachable evidence that any *permanent* change in temperature is taking place, or has taken place within historic times, in the United States. Periodicities of varying lengths of years have been suggested by numerous writers. The results differ widely. There is general agreement in the case of the Brückner thirty-five-year period. In his studies of this period Brückner has shown that there has been a coincidence between the oscillations of climate on the one hand and the flow of immigration into the United States and the settlement of the Far West on the other.[2] The amount of temperature-difference, where such has been reported, is relatively very slight and furnishes no basis as yet for making reliable scientific long-range forecasts of general economic value. A discussion of these investigations cannot be entered into here. The first thorough study of this subject was made by Schott, in his monumental analysis of the temperatures of the United States, in which he collected, reduced, and discussed all the older records.[3] Nothing was found which led to the view of any progressive change, although there was evidence of similar fluctuations of temperature over considerable areas, — for example, a period of about twenty-two years on the Atlantic coast and one of about seven years in

[1] See in this connection E. H. Bowie, "Long-Range Weather Forecasts," in "Weather Forecasting in the United States," *U. S. Weather Bur. No. 583* (1916), pp. 341–348; C. F. Brooks, "World-Wide Changes of Temperature," *Geogr. Rev.*, Vol. 2 (1916), pp. 249–255; idem, "Ocean Temperatures in Long-Range Forecasting," *M. W. R.*, Vol. 46 (1918), pp. 510–511; W. J. Humphreys, "Physics of the Air" (1920), pp. 614–625; J. Hann, "Lehrbuch der Meteorologie" (3d ed.), 1915, pp. 637–644; E. A. Beals, "Meteorological Centers of Action in the North Pacific Ocean" (abstract), *M. W. R.*, Vol. 49 (1921), pp. 330–331.

[2] E. Brückner, "The Settlement of the United States as Controlled by Climate and Climatic Oscillations," *Memorial Volume, Transcontinental Excursion of 1912, Amer. Geogr. Soc.* (1915), pp. 125–139.

[3] C. A. Schott, "Tables, Distribution and Variations of the Atmospheric Temperature in the United States and some Adjacent Parts of America," *Smithson. Contr. to Knowl.*, Vol. 21 (1876), pp. 302–320.

the interior. The long record of the opening and closing to navigation of the Hudson River at Albany, New York, indicates no progressive change in these dates.

Some twenty years ago W. B. Stockman compiled temperature data for ten stations, mostly east of the Mississippi River, covering fifty years.[1] The conclusion was that "the contention that the winters of recent years are less rigorous than those of former years, at least so far as temperature is concerned, is not well founded."

In a study of temperature variations in the United States Henry investigated the question to what extent periods of abnormally high and low temperatures synchronize, and also whether or not there is evidence of a periodicity in the occurrence and recurrence of these phenomena.[2] The data covered the period 1888–1919. It appears that in the United States the range in temperature from the year of highest temperature at sun-spot minimum (1900) to the year of lowest temperature in a year of sun-spot maximum (1917) amounted to 2.5° F. "The bulk of the evidence points to a period of between three and four years, or a third of the sunspot cycle, as being (the length of the period of oscillation) most commonly experienced."

Highest and Lowest "Record" Temperatures.[3] Great popular interest always attaches to the "record" highest and lowest temperatures. Obviously, the longer the period of observation the higher and the lower these absolute maxima and minima will respectively be. Fig. 47, which supersedes all the older charts of absolute minima, shows the lowest tempera-

[1] W. B. Stockman, "Invariability of our Winter Climate," *M. W. R.*, Vol. 32 (1904), pp. 224–226.

[2] A. J. Henry, "Temperature Variations in the United States and Elsewhere," ibid., Vol. 49 (1921), pp. 62–70. See also idem, "Sun Spots and Terrestrial Temperature in the United States," ibid., Vol. 51 (1923), pp. 243–249.

[3] Henry has given (*U. S. Weather Bur. Bull. Q*, Table II, pp. 88–92) the absolute maximum and minimum temperatures for selected stations, with the year of occurrence, for the period 1871–1903. More recent and fuller data will be found in the regular monthly and annual summaries published by the Weather Bureau. The absolute minima during the period 1871–1913 are shown in Fig. 64, p. 146, of "Weather Forecasting," *U. S. Weather Bur. No. 583*, 1916. The present Figs. 47 and 48 are redrawn from the charts of absolute minima and absolute maxima in the *Atlas of American Agriculture*. For information about the available charts reference may be made to R. DeC. Ward, "Bibliographic Notes on the Temperature Charts of the United States," *M. W. R.*, Vol. 49 (1921), pp. 277–280.

tures ever observed in the United States and is based on the records of about six hundred stations. The lowest readings of standard thermometers under proper conditions of exposure (−60° and a few degrees below) have occurred over the northernmost Plains, the gateway through which cold waves from western Canada enter the United States. Temperatures low enough to freeze mercury (−40°) have been recorded as far

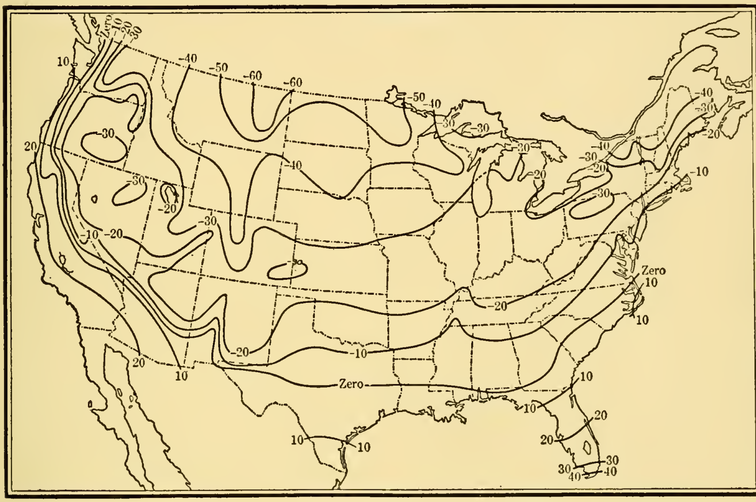

FIG. 47. Lowest Temperatures Ever Observed

south as western central Colorado, northeastern Nebraska, and central Minnesota and Wisconsin. Minima below zero have been observed over a large part of the United States. Starting from the Atlantic coast at the latitude of southern Virginia, the line along which zero temperatures have been recorded runs southwest, at some distance inland from the ocean, to northwestern Florida. It then roughly parallels the Gulf coast; crosses Texas north of latitude 30° N.; turns northwest across southwestern New Mexico and central Arizona; keeps at first east of the Sierra Nevada-Cascade Mountains, then along them, and finally crosses to the west of them. It ends in western Washington, but does not touch

the actual Pacific coast. Zero has not been recorded on the Atlantic coast south of Chesapeake Bay, on the immediate Gulf coast, or in the valley of California.

It is a striking fact that the absolute minima over the northern Plateau west of the Rocky Mountain barrier and also those along the eastern base of this barrier are distinctly higher than those over the northern Plains, in spite of lower elevations in the latter district. The effect of the barrier is here clearly seen. During inversions of temperature, which characteristically accompany the occurrence of the lowest minima, elevated stations are often considerably warmer than those close by, on lowlands or in valleys. Similarly, the advance of cold from the northern Plateau districts to the Pacific coast is prevented by the barrier of the Sierra Nevada-Cascades. Key West, Florida, is now the only regular Weather Bureau station at which no minimum temperature below freezing has been recorded. The North is not, however, under all conditions colder than the South. There are cases, by no means extremely rare, when the southern tier of states is temporarily having colder weather than those to the north.

There is a considerable tempering of the extreme cold to leeward of the Great Lakes, as is shown by the warping of the lines of equal absolute minima; for example, along the southern shores of Lakes Erie and Ontario and along the eastern shore of Lake Michigan. During severe winter cold waves the lee shores of these lakes may have temperatures 10°–20° or so higher than those observed at the same time on the opposite (windward) shores.[1] Alexander Winchell, by means of his lines of equal absolute minima, first showed in a striking way the moderating influence of the Great Lakes, especially of Lake Michigan, upon the winter temperatures in their vicinity.[2] As shown by Eshleman in a much later study, the absolute mini-

[1] See, for example, E. T. Turner, "The Climate of the State of New York," *Fifth Ann. Report Met. Bur. and Weather Service of the State of New York* (Albany, 1894), p. 370; idem, "The Climate of New York," *Bull. Amer. Geogr. Soc.*, Vol. 32 (1900), pp. 118–119. Also "Weather Forecasting in the United States," *U. S. Weather Bur. No. 583*, pp. 151–152, and Mark Jefferson, "The Great Lakes in a Cold Wave," *Journ. Geogr.*, Vol. 12 (1914), pp. 221–223.

[2] Alexander Winchell, "The Isothermals of the Lake Region," *Proc. Amer. Assoc. Adv. Sci.*, Vol. 19 (1870), pp. 106–117.

mum temperatures at Grand Haven in winter (November–January) run higher by about 10° than those at Milwaukee, and by about 12°–16° (October–January) higher than those of a group of western inland stations on the same latitude.[1] "Whole weeks of zero weather occur in Wisconsin and Minnesota when the temperature at Grand Haven will not go below 15° or 20°." The lake influence is clearly seen in the occurrence of an

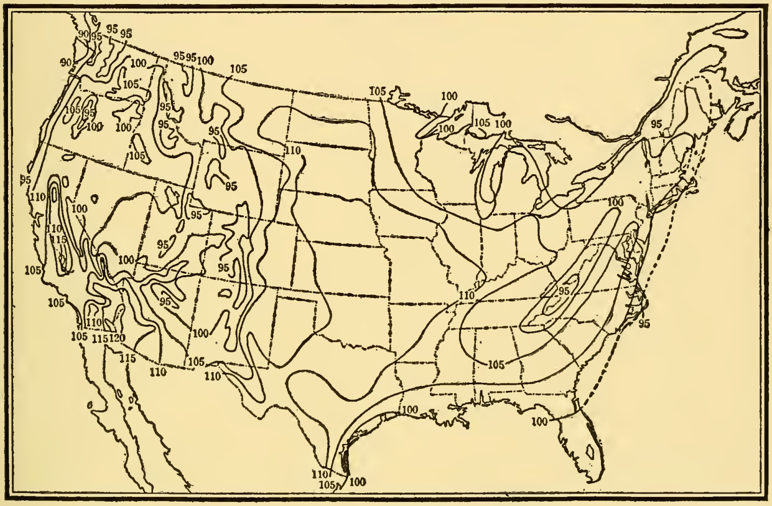

FIG. 48. Highest Temperatures Ever Observed

extended and important fruit belt which reaches from the southwestern corner of the state along the eastern shore of Lake Michigan as far as Grand Traverse Bay.[2] The famous peach region of Michigan forms part of this same belt.

The absolute maxima (Fig. 48) are surprisingly uniform over the United States as a whole. The differences are slight, and the lines of equal absolute maxima show no such well-defined system as is the case with the minima. For purposes of broad generalization and of easy memorizing it is perhaps enough to say that extreme temperatures of over 100° have been observed

[1] C. H. Eshleman, Meteorological Chart of the Great Lakes, *U. S. Weather Bur.*, September, 1913.

[2] A. J. Henry, *U. S. Weather Bur. Bull. Q*, p. 556.

over most of the United States. The exceptions are the immediate northern coasts of the Atlantic and Pacific oceans, portions of the lake region, central and southern Florida, the Texas coast, northern New England, and the higher parts of the mountain areas. Over all these last-named districts the readings are from somewhat under 95° to a little under 100°. The tempering influences of the Great Lakes are again seen in the deflection of the lines of equal absolute maxima. The values are roughly 10° less on the eastern shore of Lake Michigan than on the western shore. Grand Haven has summer maxima lower by 6°–7° than those of Milwaukee and by 10°–15° lower than those of a group of western continental stations.[1] "A difference of 10° to 20° in the maximum temperatures (at Grand Haven) compared with inland stations on warm days is a common occurrence." The highest readings for the country as a whole exceed 120° in southwestern Arizona. Maxima over 115° occur, over a larger district, in southeastern California and southeastern Arizona, as well as in the valley of California. The "record maximum" is 134°, recorded at Greenland Ranch, on the edge of Death Valley, California (July 10, 1913).[2] Owing to the small scale of the map the high temperatures in Death Valley are not indicated. Almost every summer the highest temperatures recorded in the United States occur at Greenland Ranch. It should be added, however, that the excessively high maxima of the far Southwest are associated with relatively dry air, and are far less oppressive and less dangerous than the lower maxima in the moister air of the East.

The Average Lowest Temperature of the Year. The average lowest temperature reading of the year (mean annual minimum) not only has a general popular interest but is also important because of certain of its economic relations. The new chart of average annual minimum temperatures (Fig. 49) replaces a far less complete one published by van Bebber in 1893.[3] A thermometer reading below –30° is a normal winter

[1] C. H. Eshleman, loc. cit.

[2] G. H. Willson, "The Hottest Region in the United States," *M. W. R.*, Vol. 43 (1915), pp. 278–280; A. H. Palmer, "Death Valley — The Hottest Known Region," ibid., Vol. 50 (1922), pp. 10–13.

[3] Reproduced in the *Atlas of Meteorology*, 1899, Plate 2.

occurrence over the northern Plains and northern Minnesota. Northern New York and northern New England have –25°. Temperatures below zero are to be expected on the coast as far south as southern New England, southern New York, and northern New Jersey. From this section the line of mean annual minimum of zero runs in a general southwesterly direction across Maryland, Kentucky, northern Tennessee, southern

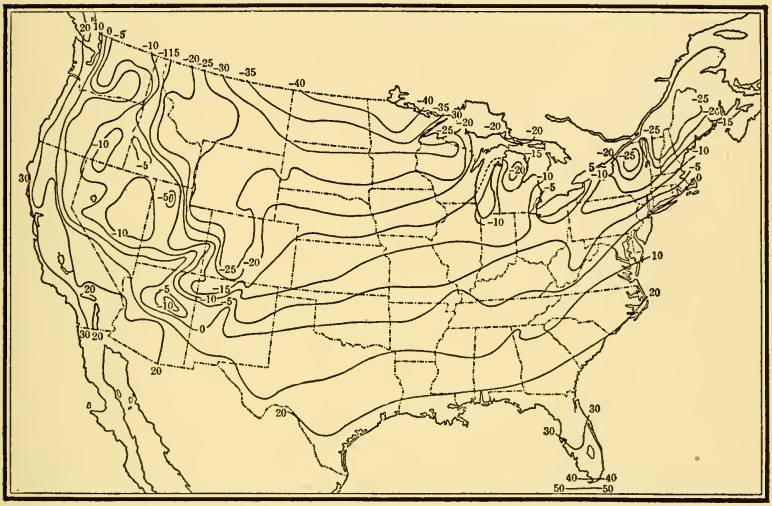

FIG. 49. Average Annual Minimum Temperatures

Illinois and Missouri, northern Arkansas, Oklahoma, and northern Texas into eastern New Mexico. Thence it turns west and northwest, following along the eastern slopes of the Pacific coast ranges and ending in eastern Washington. The Gulf states have minima mostly between 10° and 20°, with above 20° over all Florida and along the Texas coast. The tempering of the cold by latitude is thus clearly indicated. Topographic controls are seen in the positions of the lines over the western plateau and mountain districts; for example, in Colorado, New Mexico, and Arizona. The Rocky Mountains obviously act as an effective barrier against the penetration of extreme cold from the northern Plains into the Plateau districts. No

cold of eastern intensity is indicated in any portion of the great district to the west of the Rocky Mountains. The Pacific coast is further protected by the Sierra Nevada-Cascade barrier against the invasion of low temperatures from the east. On the immediate Pacific coast the mean annual minima are somewhat over 20° in the north and somewhat over 30° in the south.

The irregularities of the lines in the lake region, especially in the case of Lake Michigan and of the lower peninsula of Michigan and of the lee shores of Lakes Erie and Ontario, show a very obvious tempering effect of the lake waters.[1] The mean monthly minima at Grand Haven, Michigan, run about 4°–6° higher than those at Milwaukee, Wisconsin, during the winter, and 10°± higher than those of a group of inland stations somewhat farther west.[2]

One of the striking, and also one of the serious climatic characteristics of the eastern United States is the temporary and sudden penetration of very low minima far to the south, into latitudes where the winters are distinctly mild. This condition occurs in connection with the advance of a cold wave from north and west. A general knowledge of the mean annual minimum temperatures is here essential to a full appreciation of the climatology of this area. Hann pointed out that the temperature at New Orleans falls each winter on the average nearly to 20°, whereas at Cairo, in the same latitude, it reaches only a degree or so less than 40°; yet both mean annual and mean January temperatures at these two cities are essentially the same.[3] And over half a century ago Russell noted the fact that Savannah, Georgia, has a mean winter temperature similar to that of May in London and of winter in Cadiz, which is 4.5° of latitude farther north.[4] Yet the vegetation of southern Spain is quite different from that in North America because of the higher winter minima in the former country. In a case like this vegetation becomes a better index than is the mean temperature. Oranges are liable to serious damage by frost over

[1] See, for example, J. Hann, "Atlas der Meteorologie" (1887), text page 5.

[2] C. H. Eshleman, loc. cit.

[3] J. Hann, "Atlas der Meteorologie" (1887), text page 5.

[4] Russell, "North America, its Agriculture and Climate," 1857. Quoted by J. Hann, "Handbuch der Klimatologie," Vol. 3 (3d ed., 1911), p. 364.

nearly all the southern United States; not so in southern Spain. Cotton is replanted annually in the United States; not so in Spain. It is true that spells of considerable cold also invade low latitudes in eastern Asia, but there the mean winter temperatures are lower than in the eastern United States.

The mean annual maxima have much less human and economic significance than the mean annual minima.[1]

Other Facts concerning Annual and Monthly Maxima and Minima.[2] The differences which have been recorded between the highest and lowest temperatures ever observed are worthy of note. These differences are of the order of 150° in the north-central districts of the interior; 125° in northern New England and the lower lake region; less than 100° along the Gulf coast; about 50° at Key West; 120° in the Rocky Mountain and Plateau region generally; in the southwestern interior, 110°; less than 100° on the Pacific coast, with the exception of the Columbia River valley and the mountains.[3] During a single month differences of the order of 100° may occur over the northern interior in winter, between the extreme cold of a cold wave and the high temperatures of a warm spell. Although these monthly ranges decrease rapidly to the south, they are greater than those of central Europe at least as far as latitude 40° N. (Hann).

Temperature Changes during Twenty-four-Hour Intervals. Two places with the same average daily temperatures may differ very much in the physiological effects of these temperatures. One station may have a very considerable difference between its daily maximum and its daily minimum, whereas

[1] No chart of mean annual maxima has been published since that of van Bebber in 1893.

[2] The complete numerical presentation of highest and lowest temperatures requires several columns in a standard climatic table. See, for example, J. Hann, "Handbook of Climatology," Vol. I (2d ed., English translation by R. DeC. Ward), table on page 33.

[3] A. J. Henry, loc. cit., pp. 29–30. No map of the mean annual extreme range has been constructed since that of van Bebber, for the world (*Atlas of Meteorology*, Plate 2). These ranges, also known as the *mean annual non-periodic ranges*, average about twice as large as the *mean annual periodic ranges* previously referred to, which are based on the differences between the mean temperatures of January and of July.

the other has a fairly uniform temperature day and night. Obviously the effects upon human activities, and comfort or discomfort, will be quite different in the two cases. Hence the importance of knowing something about the temperature changes during the twenty-four-hour interval. There are two fundamental types of temperature changes during the conventional twenty-four-hour time unit. One is the normal change, on fine days with marked solar control, from just before sunrise to shortly after noon—from a cool night to a warm afternoon. The other is the irregular change not related to the time of day, due to winds, clouds, etc., and resulting from cyclonic or anticyclonic controls. There are obviously all varieties of combinations of these two types. The first, that is, the so-called normal diurnal type, is chiefly characteristic of the semi-arid western Plateau district, where a prevailing small amount of cloud, dry air, and sparse vegetation favor strong sunshine by day and active radiation at night, but is also a common feature elsewhere, especially during the warmer months and in the Southern states. The second, the irregular cyclonic type, is mainly characteristic of northern and eastern sections. It is also relatively frequent during the colder months everywhere, being least marked on the southern Pacific coast and in the South and Southwest. This type is best developed when the cyclonic control is strongest, in winter, but occurs with reasonable frequency, although with greatly diminished intensity, in connection with the weaker cyclonic control of summer. Blodget first clearly emphasized the fact that the regular diurnal (that is, solar) control is dominant in the West, while changes "of what may be called the greater non-periodic sort" distinguish the East. "Extreme contrasts, diversities, and transitions belong here (in the interior) to *place* or *locality*; in the East to *time*." This is a significant statement. It emphasizes the importance of the regularity of the solar control and of the part played by the topography in the West. In the East, per contra, the time of the arrival and departure of cyclone or anticyclone is the deciding factor.

The common designation for the temperature-differences

which occur during a day is the diurnal range.[1] The greatest daily ranges of temperature, resulting from the normal warming by day and cooling by night, occur over the western Plateau Province and in summer. Here, in July, practically the whole area has average daily ranges over 30°, and much of it has ranges of over 35°. Differences of 50° between early morning and noon are not uncommon. Individual cases of a rise from near the freezing-point to 80° and even to 90° are on record. Over the Eastern Province the daily ranges are considerably less. They decrease from about 30° over the Plains (July) to less than 20° over the Great Lakes, along the Atlantic and Pacific coasts, and over the Gulf Province. On much of the immediate Atlantic, Gulf, and Pacific seacoast the ranges are under 15°. The daily temperature ranges of summer over the eastern interior are relatively small, considering the continental climate and the high temperatures. Hann has attributed this fact to the high humidity of summer, which gives an almost tropical character to the climate at that season—a climate marked by relatively small daily ranges of temperature.[2] The average daily temperature ranges for January are on the whole smaller than in July, especially over the western Plateau Province, where the diurnal control is least marked in midwinter.

The sudden, irregular temperature changes which occur under

[1] When the difference between the mean temperatures of the warmest and coldest hours of the day is given, it is known as the *periodic diurnal range*. When the difference between the mean daily maxima and the mean daily minima (determined from readings of the maximum and the minimum thermometers on individual days) is given, it is known as the *non-periodic diurnal range*. The latter is the one usually given in climatic tables and discussions. It is determined much more easily and, for all practical purposes, may be used instead of the periodic range. When hourly temperature data are available, the periodic range is easily worked out. In connection with this see Alexander McAdie, "Mean Temperatures and their Corrections in the United States," 1891; tables of mean hourly temperatures for regular Weather Bureau stations for the five years 1891–1895, in *Annual Report of the Chief of the Weather Bureau for 1896–1897*, pp. 94–107; also a short table of mean diurnal periodic ranges, based on McAdie's report, given by Hann in his "Handbuch der Klimatologie," Vol. 3 (3d ed., 1911), p. 363. The Temperature section of the *Atlas of American Agriculture* contains four charts (Figs. 81–84) showing the average daily range of temperature for January, April, July, and October, and also curves showing the daily march of temperature for selected stations for the same months (Fig. 85).

[2] J. Hann, "Handbuch der Klimatologie," Vol. 3 (3d ed.), p. 362.

cyclonic and anticyclonic control and are chiefly characteristic of the East may be as great as those which are due to normal diurnal control in the West. Thus, a winter warm spell with southerly winds may be followed within twenty-four hours or less by a cold wave with temperatures 50° or more lower. Remarkably sudden temperature changes also occur in connection with chinook winds along the eastern base of the Rocky Mountains. Or in summer, during a hot wave, the advance of a cyclonic cloud sheet and the setting in of cool easterly winds on the Atlantic coast "breaks" the heat within a few hours, bringing welcome relief. Several different types of weather bring these "paroxysms of change" (Blodget).

The Differences in Temperature from Day to Day. There are two fundamental controls determining the differences in temperature from one day to the next. One is regular; the other, irregular. The first is the sun. Under the sun's control alone each day should normally be a little warmer than the preceding day during the warming half of the year, and a little cooler during the cooling half. The second is the cyclonic and anticyclonic control. This is irregular, varying with the temporary conditions of pressure distribution and the accompanying temperature, winds, clouds, and rain. The second of the two controls is by far the more important over most of the United States and most of the time, especially during the colder season. It brings marked and sudden temperature changes from day to day, completely upsetting the orderly seasonal advance and retreat. These day-to-day changes in temperature are of great importance in relation to human comfort and health. They markedly affect a wide range of man's activities. The conventional method of expressing such changes is to give for each month the average difference between the mean temperatures of successive days.[1] In a table compiled

[1] *Mean diurnal variability of temperature;* that is, the mean of the differences between successive daily means. Data regarding this factor have been worked out for comparatively few stations in the United States. See tables of Average Daily Variability of Temperature (for eighteen selected stations) and of Average Daily Variability of Temperature in Percentages (Washington, D. C., 1883–1903), in *U. S. Weather Bur. Bull. Q*, p. 33. Also *Annual Report of the Chief of the Weather Bureau for 1896–1897*, p. 284.

by Supan some years ago it appears that the interior of North America, including the northernmost parts of the United States, is one of the two centers of maximum diurnal variability in the Northern Hemisphere.[1]

Generalizing broadly it may be stated that the mean diurnal variability in winter is of the order of about 10° in the northern central interior, and decreases from there in all directions, to about 2.5° on the north Pacific coast and 2° on the south Pacific coast, a little over 5° on the Gulf coast, and about 3° in southern Florida.[2] The decrease from the interior to the Atlantic coast is relatively slight, because this leeward coast shares so largely in the continental conditions of the interior. The lines of equal variability follow the lines of absolute minimum temperatures with reasonable closeness, indicating a dependence of the large diurnal variability of winter upon the occurrence of cold waves. The mean diurnal variability in summer is usually about one half of that in winter. It should be observed that the foregoing data refer to differences between the daily *mean* temperatures, and not to the total amount of rise or fall of temperature from day to day. Such irregular changes are of especially striking frequency and of large values in the northern United States east of the Rocky Mountains in winter, reaching 50° or even more within twenty-four hours.

Several factors combine to bring about these rather remarkable irregular temperature changes in the eastern United States: the rapid winter poleward temperature gradient; the presence of the warm Gulf of Mexico in the south; the Gulf Stream off the east coast, and the cold continent to the north; and the frequency, intensity, and rapid progression of cyclones and anticyclones. Under the control of the rapidly changing pressure gradients as highs and lows pass by, the winds are constantly changing their direction. Thus, large masses of air, often moving at high velocities, are imported from districts of widely varying temperatures—now from the warm Gulf of Mexico;

[1] A. Supan, "Grundzüge der Physischen Erdkunde" (3d ed.), 1903, p. 99.

[2] See chart prepared by General A. W. Greely, "Variability of Average Daily Temperature in January," reproduced in F. Waldo's "Elementary Meteorology" (1896), Fig. 101, pp. 330–332.

now from the cold plains of western Canada; now from the Atlantic Ocean on the east. Marked and sudden changes in temperature and in general weather conditions are therefore inevitable. Furthermore, winds not only control temperatures directly, by the actual importation of warm or of cold air, but also indirectly, by bringing clear skies and thus increasing the local production of cold by nocturnal radiation on quiet nights and the warming under sunshine by day; or by bringing clouds and rain, and thus cutting off sunshine by day and checking terrestrial radiation by night.

Does the Annual March of Temperature show Persistent Irregularities? There is a widespread popular belief in the recurrence, about the same time every year, of longer or shorter periods of unseasonable cold or heat. Among these "spells" of weather the ones most commonly referred to in the United States are the "January thaw," a cold period about the middle of May, and the "Indian summer." Marvin recently investigated this question by making a study of the temperature records for several long-period stations in the northeastern United States, supplemented by forty-five-year records from Weather Bureau stations scattered over the country.[1] The conclusion reached was that the annual record of daily mean temperatures is a smooth curve, without secondary maxima or minima or perceptible points of inflection, and that such marked irregularities as are described by the terms "January thaw" or "May freeze" neither persist nor do they have a real existence. In cases where these or similar irregularities appear in the means, they were believed to be the effect of a single occurrence or of a few accidentally recurrent unusual or extreme events near or at the time in question.[2] A study of the

[1] C. F. Marvin, "Are Irregularities in the Annual March of Temperature Persistent?" *M. W. R.*, Vol. 47 (1919), pp. 544–555. The same number of the *Review* also contains a useful annotated bibliography of this subject (pp. 555–565) by C. F. Talman.

[2] In a letter dated March 24, 1925, Professor Marvin wrote as follows, qualifying some of the conclusions stated in this article:

"The impression that conspicuous irregularities in the annual march of temperature are due primarily to accidental large departures, which can only be effaced afterwards by departures of an opposite character or by a very long record of normal values, calls for qualification to the extent that, at least for some of

long-period temperature records kept at New Bedford, Massachusetts, between 1813 and 1905, was made by the late W. E. Forbes.[1] The object of this investigation was to discover evidence for or against the occurrence of a cold spell in New England about May 10 ("Ice Saints"). It appears that cold weather as well as hot may be expected on May 10, and hot weather as well as cold on May 7 or May 13. "It is nevertheless possible that when the pulsations of the weather are better understood, May 10 may prove to be a sort of node and may serve as a point of departure for the study of weather waves."[2]

these irregular features, at certain places in the year not only large departures occur but the number of departures in one direction are distinctly predominant. It seems a question, therefore, if even a record of a thousand years, for example, would produce the smooth annual march of temperature which we ordinarily call a normal and which would be represented by the harmonic equation of three or four terms which has been used by me. Indeed, two terms are sufficient for eastern and northeastern states in the United States, but it has been found that interior and certain other stations are better represented by four-term equations.

"From the bulk of evidence now available I am inclined to believe that the last week in January over the northern, eastern, and central sections of the United States is likely to be predominantly above a smooth ideal normal march of temperature, and that the week beginning about February 1, on the contrary, is likely to be predominantly below a smooth curve of the character mentioned. I think the human mind knows no reason why there should be an irregularity of this character, and that we think of the normal march of temperature in terms of the smooth ideal line represented by our mathematical equation, for example. Therefore, our personal experience justifies us in believing there is such a feature as a warm spell at the close of January, followed by a colder spell in the week following.

"I think there may be other places in the year in which conspicuous alternations of temperature occur, consequently a record of several hundred years would still show sinuosities which would call for explanation, because we are compelled to think of the normal temperature as a smooth progressive curve. All the details necessary to settle a question of this character can be worked out only with great care and labor in handling a large body of statistical data, and this necessarily takes time."

[1] W. E. Forbes, "Ice Saints," *Ann. Astron. Obs. Harvard College*, Vol. 83, Part I (1917), pp. 53–59.

[2] An early discussion of this subject may be found in "Tables, Distribution and Variations of the Atmospheric Temperature in the United States and Some Adjacent Parts of South America," by C. A. Schott, *Smithson. Contr. to Knowl.*, Vol. 21 (1876), pp. 192–194.

CHAPTER VI

FROST

FROST MAPS OF THE UNITED STATES · NATURE AND OCCURRENCE OF FROST: THERMAL BELTS · THE LAST KILLING FROST IN SPRING · VARIATIONS IN THE DATES OF SPRING FROSTS · THE FIRST KILLING FROST IN AUTUMN · AVERAGE LENGTH OF THE GROWING SEASON · GENERALIZED SUMMARY OF FROST DATES

Frost Maps of the United States. In the previous chapter reference was incidentally made to the occurrence and distribution of temperatures below 32°. In the present chapter the larger facts concerning frost are considered. There have been three general stages in the charting of frost in the United States. In the earlier maps the average dates of the first and last killing frosts were based solely on records obtained at regular Weather Bureau stations.[1]

A second stage was reached when, in addition to the data obtained at the regular stations of the Weather Bureau, observations made by coöperative observers widely scattered over the country were also taken into account. By the inclusion of these additional data a much more accurate and more complete view of frost conditions was gained. Maps based on this larger series of observations, including those made at approximately

[1] A. J. Henry, "Climatology of the United States," *U. S. Weather Bur. Bull. Q* (1906), pp. 33–34, Plates XIX and XX. See also previous charts in A. W. Greely's "American Weather" (1888), pp. 269–270, frontispiece, and Chart XXIII. These maps were reproduced in F. Waldo's "Elementary Meteorology" (1896), pp. 333–335, Figs. 103 and 104. In all these maps the lines of equal frost dates were left incomplete over much of the West, owing to the lack of adequate information, but in the later maps of this first stage (1906) the average dates of the first and the last frost were entered at certain Weather Bureau stations over the western plateau and on the Pacific coast, although the lines themselves were not drawn. The information given on all these maps was obviously based on very insufficient data. Observations at regular Weather Bureau stations, located chiefly in large cities, do not show actual conditions of frost occurrence over the rural farming districts and are also too few in number for accurate generalization.

a thousand coöperative observers' stations having the longest records (usually about ten to thirty years), were published in 1911.[1]

A third stage has been reached in the publication of the very valuable and comprehensive study of frost which forms part of the *Atlas of American Agriculture.*[2] Frost records are now available from about four thousand regular and coöperative stations of the Weather Bureau. About six hundred of these cover a period of twenty years (1895–1914), which was adopted for most of the climatic material in the new *Atlas*; about eighteen hundred cover over ten years but less than twenty; and the remaining sixteen hundred are for shorter periods, none less than five years. All these data have been verified by experts familiar with the locations of the various stations and with the surrounding districts. This monograph contains numerous diagrams and maps, mention of which is impossible here, and also a short bibliography.[3]

[1] P. C. Day, "Frost Data of the United States and Length of the Crop-Growing Season. As Determined from the Average of the Latest and Earliest Dates of Killing Frost," *U. S. Weather Bur. Bull. V*, 1911. This investigation included maps of the average dates of the first and the last killing frost, of the earliest and latest dates on which killing frosts have occurred in autumn and spring respectively, and of the average length of the crop-growing season. This new set of maps brought out the influence of local conditions upon frost occurrence much more clearly than had been done before. Lines were drawn for the eastern sections, but dates only were still used over the western mountain and plateau districts and on the Pacific slope.

[2] W. G. Reed, "Frost and the Growing Season," in *Atlas of American Agriculture* (prepared under the supervision of O. E. Baker, Office of Farm Management, U. S. Dept. of Agriculture), Part II, Sect. 1, 1918. This publication presents the whole subject of frost with a detail not hitherto attained in any other area of equal size anywhere in the world.

[3] See also W. G. Reed and Cora L. Feldkamp, "Selected Bibliography of Frost in the United States," *M. W. R.*, Vol. 43 (1915), pp. 512–517. Three additional papers by W. G. Reed have been published as follows: "Outline for the Study of Frost and Protection against Frost Damage," *Journ. Geogr.*, Vol. 14 (1915–1916), pp. 54–55; "Protection from Damage by Frost," *Geogr. Rev.*, Vol. 1 (1916), pp. 110–122; "Frost in the United States," *Proc. 2d Pan-Amer. Sci. Congr., Washington, U.S.A., December 27, 1915, to January 8, 1916*, Sect. II, Vol. II (1917), pp. 593–631. A selection of books and papers bearing on frost forecasting was printed in "Weather Forecasting in the United States," *U. S. Weather Bur. No. 583* (1916), pp. 357–358. An important study of the occurrence of frost over the earth as a whole is that of Otto Dorscheid, "Die mittlere Dauer des Frostes auf der Erde," *Met. Zeitschr.*, Vol. 42 (1907), pp. 11–24, 49–64 (with maps of frost dates).

Nature and Occurrence of Frost: Thermal Belts. Frost is not a simple phenomenon. It appears in varying degrees of severity ("light," "heavy," "killing"), and the line between these is not easily drawn. A frost of a certain type of severity does not necessarily cause the same amount of injury to all kinds of vegetation. Temperatures low enough to injure plants often occur without any frost deposit. Again, frost is characteristically "patchy" in its occurrence. Given generally favorable weather conditions, its actual occurrence is largely a matter of topography and of air drainage. As frost is more common and more severe on lowlands and in valley bottoms than on higher ground, it is usually safer to plant early and tender crops on hill slopes and to put the later and hardier crops at the lower levels and in the valleys. This fact is well known in hilly and mountainous regions. Vegetation on hill or mountain slopes is often uninjured when that at lower levels is seriously damaged. Such frostless areas, called "thermal belts" or "frostless zones," have been especially well studied in the mountains of North Carolina, where they attracted attention many years ago and where they have striking relations to the fruit industry of the region.[1] A recent detailed study of these conditions has been made by Cox.[2] It is clear that in the area investigated valley floors and frost "pockets" should almost always be avoided for orchard sites, as their temperatures on critical nights often fall 15° or 20° and sometimes even 25° or 30° below those higher up on the slopes.

Frosts in winter have little or no economic importance except in the South and the Southwest. In summer they do not occur except in certain elevated areas. Thus it is that spring and autumn frosts are of such critical significance. For frost to occur the general weather conditions must be favorable. These

[1] J. W. Chickering, Jr., "Thermal Belts," *Amer. Met. Journ.*, Vol. 1 (1884–1885), pp. 213–218.

[2] H. J. Cox, "Weather Conditions and Thermal Belts in the North Carolina Mountain Region, and their Relation to Fruit Growing," *Annals Assoc. Amer. Geographers*, Vol. 10 (1920), pp. 57–68; "Thermal Belts and Fruit Growing in North Carolina," *M. W. R. Suppl. No. 19*, 1923. The last-named publication also contains a brief discussion of "Thermal Belts from the Horticultural Viewpoint," by W. N. Hutt (pp. 99–106, with a selected bibliography). An abstract of Professor Cox's paper will be found in *M. W. R.*, Vol. 51 (1923), pp. 199–207.

are now reasonably well understood as the result of long experience in forecasting. Type maps, characteristic of frost weather, may be selected for the various sections of the country.[1] These are very useful for purposes of local frost study and in general teaching. Indeed, the investigation of frost must be highly intensive and very local. Every area has, in a sense, its own special and peculiar frost conditions and needs its own special thermal survey. Hence no detailed discussion of frost occurrence in the United States can here be attempted.

By reference to the mean daily minimum temperatures for any station it is easy to determine the date on which, in the general course of the seasonal decrease of temperature in autumn, this minimum falls below freezing. Similarly in the spring the average date on which the mean daily minimum rises above freezing may be determined. If first and last frosts came regularly on these dates the whole frost problem would be perfectly simple. Frost, however, is characteristically variable in its dates of first and last occurrence. Cyclonic and anticyclonic spells of colder or warmer weather, coming irregularly and without much regard to the normal seasonal temperature curve, easily advance or retard the actual dates of the first and the last frost. Thus it is that there are likely to be considerable departures from the average dates, and a complete study of frost must include a consideration of these variations.

The Last Killing Frost in Spring. The accompanying figure (Fig. 50), simplified and generalized from Fig. 3 in the Frost section of the *Atlas*, gives the average dates of the last killing frost in spring as shown by the records for the twenty-year period 1895–1914. It gives the essentials of the original map, not the details. The general east-west trend of the lines in the East shows that latitude is here the chief control, although the deformation due to large bodies of water and to topography

[1] See Figs. 6–15 of the Frost section of the *Atlas of American Agriculture*, and Figs. 101–124 in "Weather Forecasting in the United States," *U. S. Weather Bur. No. 583*, 1916. A discussion of frost forecasting in various sections of the United States will be found on pp. 177–215 of the latter publication. The details are, however, hardly of climatological interest.

is also obvious.[1] In the West, altitude and the influence of the Pacific Ocean are the chief controlling factors. In view of the complex topographic controls over frost occurrence in the West, and of the further fact that the reporting stations are mostly at the lower levels, it is impossible to draw the lines of frost dates with great accuracy or detail in that region.

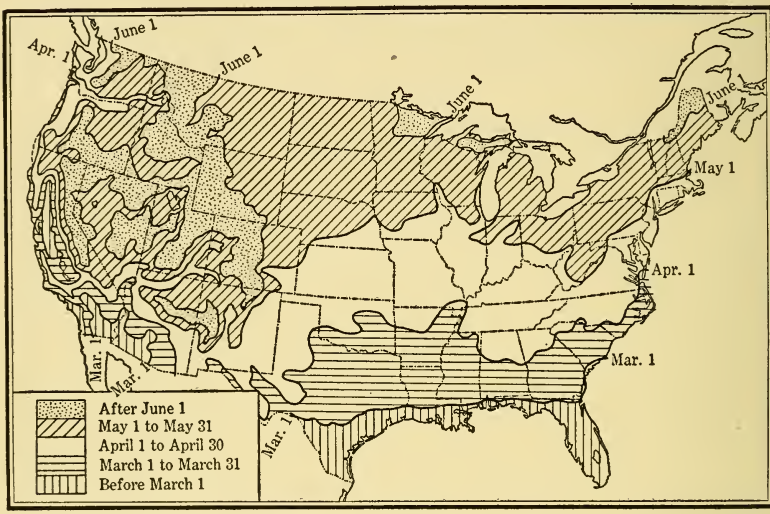

FIG. 50. Average Dates of the Last Killing Frost in Spring

The earliest date shown on the map is March 1. The area over which frost does not occur annually includes the southern half of Florida and the immediate coasts of the Gulf of Mexico and of southern California. Killing frost occurs in fewer than half the winters in southern Florida and in the region around San Diego. Excepting Key West and some of its neighboring keys, frost has occurred in all parts of the United States. Over about one eighth of the country—that is, along the

[1] Winchell first clearly pointed out the effect of the Great Lakes in shortening the frost season in the lower peninsula of Michigan, thereby making that district a climatic oasis more favorable for the growing of certain crops than other districts farther south (Alexander Winchell, "The Isothermals of the Lake Region," *Proc. Amer. Assoc. Adv. Sci.*, Vol. 19 (1870), pp. 106–117). See also Chapter V ("Temperature"), above.

northern boundary and at the greater elevations in the West—the average date of the last killing frost in spring is after June 1.

Variations in the Dates of Spring Frosts. It is a well-known fact that the actual date of the last killing spring frost is likely to depart very considerably from the average date. Late spring frosts, occurring some time after the average date of the last frost, are liable to cause heavy losses to gardeners and fruit-growers. Hence the importance of a study of the variations in the dates of spring frosts.[1] These variations are, as a rule, smaller near the Atlantic coast and over the strip of country just east of the Rocky Mountains. They are greatest to the west of the Rocky Mountains, where the local effects of the varied topography are most marked, and in Florida and along the Gulf coast. In the West, in Florida, and on the Gulf coast a killing frost coming a month later than the average date of the last killing frost (in spring) is likely to occur about one year in ten.[2]

The First Killing Frost in Autumn. Fig. 51 is a simplified and generalized reproduction of Fig. 20 in the *Atlas*. It shows the average dates of the first killing frost in the fall. The general similarity between Figs. 50 and 51 as here given is easily seen. Thus the region over which the average dates of the first killing frost are earlier than September 1 is about the same as, though somewhat smaller than, that over which the average dates of the last spring frost are later than June 1. The latest average date of the first killing frost is December 1. It is not usually till after this time that frost occurs in the Florida peninsula, on the coast of Texas, in southwestern Arizona, in southern California, and in a part of the great valley of California. The effects of the Great Lakes in delaying the date of the first killing autumn frost are clearly seen. The lake waters retain their summer heat well on into the autumn. Hence their shores have generally higher temperatures than the inland districts, somewhat removed from the

[1] This has been carried out, as fully as is now possible, in the *Atlas*. A colored map (Fig. 16) based on seven hundred records indicates the number of times in the twenty years from 1895 to 1914 that the last killing frost in spring was ten days or more later than the average date. This map therefore gives a measure of the variability of the dates of the last killing frost.

[2] *Atlas*, Fig. 23.

tempering influence of the Lakes. The detailed map upon which Fig. 51 is based shows that the first killing frosts in autumn usually come more than twenty days earlier in the northern interior of the lower peninsula of Michigan than on the shores close by.[1] Over a considerable portion of this interior the first killing frost arrives on the average before September 21. To the east, along the shore of Lake Huron,

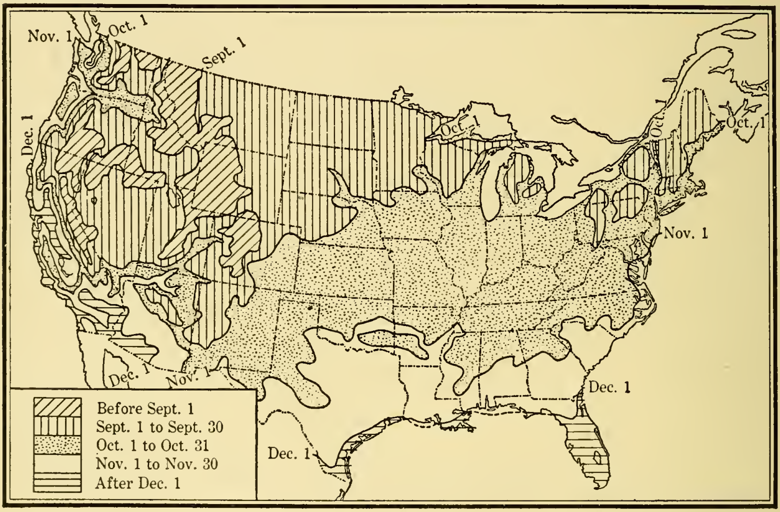

FIG. 51. Average Dates of the First Killing Frost in Autumn

the average date is after October 1; to the west, along the shore of Lake Michigan, it is after October 11. The date is most retarded in the latter case, because the prevailing westerly winds blow off the water and are somewhat warmer there than on the eastern shore, where they have blown across the cooler land. The counties bordering on Lake Michigan are naturally the fruit districts.

The first killing frost in autumn may come some days ahead of the average date. Late vegetables and other crops, as well as flowers, may then suffer serious injury.[2]

[1] Fig. 20 in the Frost section of the *Atlas of American Agriculture.*

[2] As in the case of spring frosts, above noted, two maps are given in the *Atlas* which show the variations in the dates of the first autumn frost (Figs. 18 and 25).

Average Length of the Growing Season. Fig. 52 is a simplified and generalized map showing the average length of the period without killing frost.[1] At Key West, Florida, the growing season is three hundred and sixty-five days long. Over most of Florida, on the coast of the Gulf of Mexico, and in favored localities in Arizona and California the average growing season is over two hundred and sixty days. It is about

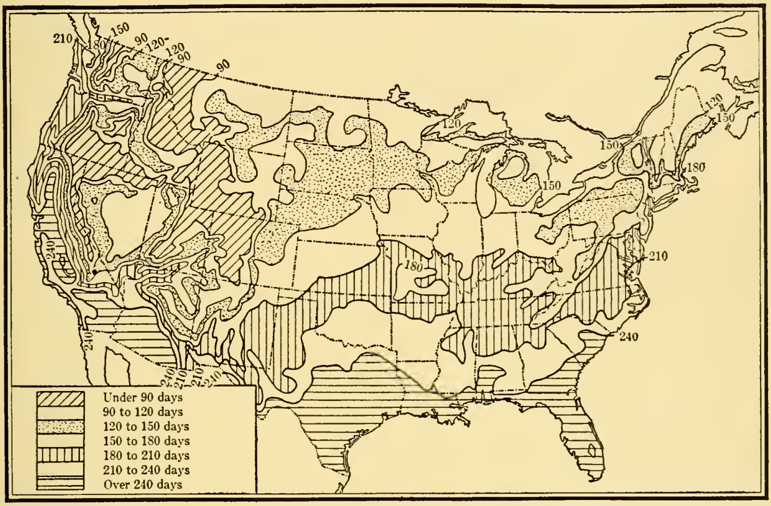

FIG. 52. Average Length of the Growing Season

two hundred days along the northern margin of the cotton belt, between one hundred and forty and one hundred and fifty days along the northern margin of the corn belt, and about one hundred days in northern Maine and northern

[1] From Fig. 29, loc. cit. Fig. 27 in the *Atlas* shows how many times in the twenty years 1895–1914 the season without killing frost was fifteen days or more shorter than the average. Fig. 32 shows the approximate length of the season available for the growth of many crops in about four fifths of the years. This gives, in general, "the number of days expected to be available for the growth of crops in a sufficiently large proportion of the years to enable the organization of farm enterprises on that basis with a reasonable chance of success." See also J. B. Kincer, "Relation between Vegetative and Frostless Periods," *M. W. R.*, Vol. 47 (1919), pp. 106–110, and Raphael Zon, "Meteorological Observations in Connection with Botanical Geography, Agriculture, and Forestry," ibid., Vol. 42 (1914), pp. 217–223.

Minnesota, where the chief crops are hay, potatoes, barley, and oats. The region with an average period of less than ninety days without killing frost, which includes the higher parts of the West, is mostly not available for general farming. Forests are found there when there is sufficient rainfall. The length of the growing season naturally varies considerably from year to year with the fluctuations in the dates of frost occurrence.

Generalized Summary of Frost Dates. For convenience of memorizing, the following very broadly generalized summary of the essential frost dates and of the average number of months with frost in the eastern United States is included.

District	First Autumn Frost	Last Spring Frost	Months without Frost
Northern belt	September	May	3
Intermediate belt	October	April	5
Southern belt	November	March	7
Gulf belt	After December 1	Before March 1	9

CHAPTER VII

PREVAILING WINDS AND THEIR CHARACTERISTICS

IMPORTANCE OF WINDS IN ECONOMIC CLIMATOLOGY · GENERAL RELATIONS OF PRESSURES AND WINDS: CYCLONIC AND TOPOGRAPHIC CONTROLS · JANUARY WINDS · JULY WINDS · MONSOONS · GEOGRAPHICAL DISTRIBUTION OF WIND VELOCITIES IN THE UNITED STATES · MAXIMUM WIND VELOCITIES · SEASONAL AND DIURNAL VARIATION IN WIND VELOCITY

Importance of Winds in Economic Climatology. To the prevailing winds many of the larger characteristics of climate are due. Winds import temperatures and moisture from a distance. If their way is not obstructed by mountain barriers, they tend to produce uniformity of climates over extended areas. They effectively wipe out many climatic boundaries. They bring marine conditions on shore. They carry land conditions off shore. They largely determine rainfall and thus control the distribution of life. They bring clean, pure air and are active agents in promoting health; or, by carrying dust and micro-organisms, they may contribute to the prevalence of disease.

Wind velocity also, apart from wind direction, has many human relations. The difference in the feeling of physical comfort or discomfort largely depends upon the amount of wind movement. The more extreme manifestations of wind force damage buildings and crops, wreck vessels, and endanger or destroy human life. A knowledge of the highest velocities that are likely to occur is essential in the work of an engineer or of an architect in the planning and the construction of buildings and of bridges.

As a source of power, winds are attracting more and more attention. There are in the United States scores of firms whose sole business it is to make windmills, thousands of which are in use. It is a significant illustration of the climatic control of

the location of an industry that most of these windmill plants are situated in the Middle West, where there is the most effective wind movement and where the demand for windmills is greatest. American inventors have perfected powerful steel windmills which are self-adjusting to varying wind directions and velocities. They make the maximum use of the minimum effective wind movement, and automatically turn out of the wind when the velocity becomes too great. In use over large sections of the United States where the wind velocities have proved themselves to be most usable and reliable, windmills are today pumping water for irrigation, for cattle, and for domestic uses; they are grinding corn, cutting wood, and churning. They are also being used to generate electrical energy which supplies heat, light, and power at a minimum expense. In times of slack wind, combustion engines started automatically, or storage batteries, may be used to keep up the supply of electricity. Winds have thus proved themselves a real climatic asset.

General Relations of Pressures and Winds: Cyclonic and Topographic Controls. The continental area of the United States lies almost entirely within what is generally known as the belt of prevailing westerly winds. These are members of the general atmospheric circulation. They would, however, blow from a general westerly direction much more distinctly if there were no North American continent, with its seasonal changes of temperature and of pressure, with its mountains and its lowlands, with its Great Lakes and its storms, to interfere with them. The local influences of the changing seasonal pressures over the continent and over the adjacent oceans are to a large extent paramount to the general control over air movement exercised by the differences of pressure between the equator and the higher latitudes. To the south, the states bordering on the Gulf of Mexico, sub-tropical already in latitude, share also in the wind system which is characteristic of tropical countries,—the trades. These trade winds, like the prevailing westerlies, find their initial cause in the great permanent differences of temperature and of pressure between equator and poles, but over the southern United States, as in

other regions also, they are greatly modified by the varying local pressure distribution.

Year after year the orderly succession of the seasons brings a warming and cooling of the continent. The pressures change systematically, not only over the continent itself but also over the adjacent oceans. And sympathetically, also, the prevailing winds show a seasonal change in their directions. But other influences play their part. The great mountain systems are barriers in the path of the winds. Mountains turn winds aside, as in the case of the prevailing westerlies off the southern Pacific coast in winter (noted by Ferrel);[1] or cause them to flow around the obstruction, as in the case of northwest and southeast winds in the Appalachians;[2] or otherwise serve as divides between winds of different directions and characteristics. The general configuration of the country; the trend of mountains and of valleys; locations to windward or to leeward of mountains or of lakes; the hour of the day or night; exposure to land and sea breezes,—all these factors have a part in controlling the winds, both in direction and in velocity. Then, varying from day to day, more temporary than any of these other controls, comes the ever-changing influence of cyclones and anticyclones. The dominance of these passing conditions over air movements is often so complete that *easterly* winds are of frequent occurrence throughout the belt of the prevailing *westerlies*. Many persons, indeed, especially along or near the northern Atlantic coast, find it difficult to believe that the prevailing winds are really from the west.[3] Easterly storms, easterly winds blowing on shore from a high pressure area off

[1] William Ferrel, "A Popular Treatise on the Winds" (1890), p. 187.

[2] Th. Hesselberg and H. U. Sverdrup, "Ueber den Einfluss der Gebirge auf die Luftbewegung längs der Erdoberfläche und auf die Druckverteilung," *Veröff. Geophys. Inst. d. Univ. Leipzig*, 2te Serie, Heft 4 (1914), pp. 102–116, 2 plates.

[3] A. G. McAdie, "The Paradox of the East Wind," *Pop. Sci. Mo.*, Vol. 85 (1914), pp. 292–295; idem, "The Winds of Boston and Vicinity," *Annals Astron. Obs. Harvard College*, Vol. 73, 1916, Part 3. C. F. Brooks has called attention to an interesting condition which occurred during the summer of 1920 on the coasts of New Jersey and of southern New England. An unusual persistence of offshore winds probably drove the warm surface water out to sea, resulting in an upwelling of colder water from below and in abnormally low temperatures for sea bathing (C. F. Brooks, "Cold Shore Water Owing to Off-Shore Winds," *M. W. R.*, Vol. 48 (1920), pp. 352–353).

the coast, even the local and relatively insignificant sea breeze, all combine to keep up this impression. Frequent as are the interruptions of the prevailing westerly winds near the surface, the upper currents follow their regular course from the west with remarkable persistence. The clouds which they carry tell this story. And so do the observations from Mt. Washington, Pikes Peak, and other elevated stations. The relation between the temporary cyclonic and the prevailing westerly winds was clearly recognized by Blodget,[1] who also saw the evidence of prevailing winds from west to east in the trend of the isotherms and in the difference in temperature and humidity on the Pacific and Atlantic sides of the continent.

The wind direction and velocity at any station, as shown on the daily weather maps, depend upon the controls just referred to, together with others, such as the local exposure of the wind instruments; for example, their height above the ground, the influence of adjacent buildings, etc. Many stations show quite persistent influences of local topography upon their wind directions, resulting from the position of a neighboring mountain, the trend of a valley, or from exposure to local mountain and valley winds.[2] The winds at northern stations, for example, are more affected by storm controls than those farther away from the main storm paths. The wind directions shown on weather maps are therefore the complex resultant of many variables. The wind arrows on these maps, as well as on the usual charts which show the monthly or annual prevailing wind direction at each Weather Bureau station, emphasize the local peculiarities of each place; they do not give the broadly generalized view of the winds which is desired in a study of the larger climatic conditions and of their controls. What we here want to know is the general sweep of the winds (the wind

[1] Lorin Blodget, "Climatology of the United States" (1857), chap. xi.

[2] T. H. Davis, "Direction of Local Winds as Affected by Contiguous Areas of Land and Water," *M. W. R.*, Vol. 34 (1906), pp. 410–413; F. B. White, "Topographic Influences on the Winds of our Weather Maps," *Amer. Met. Journ.*, Vol. 12 (1895), pp. 15–19; W. M. Davis, "Elementary Meteorology" (1894), Figs. 29 and 30, p. 98. (These figures which show the annual frequency of wind directions at Kinderhook, in the Hudson valley, trending north and south, and at Utica, in the Mohawk Valley, trending east and west, illustrate very strikingly the topographic control exerted by these two valleys on the direction of the prevailing winds.)

systems) over the different sections of the United States. In Figs. 53 and 54 the prevailing winds for January and July are thus broadly generalized. No attempt is made to show details or to insure accuracy of direction over every portion of every state. The purpose is only to give a general view of the larger wind movements. The effects of local topography have, so far as is reasonably possible, been disregarded, and in cases

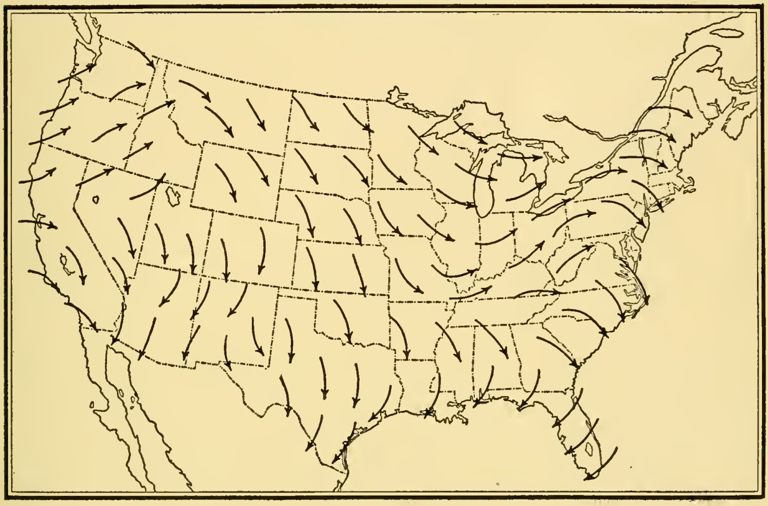

FIG. 53. Prevailing Winds in January

where several wind directions have almost equal percentages of frequency the prevailing direction has been taken to be that which agrees with the general conditions of wind movement over neighboring districts. Useful as such generalized wind charts are in a climatological study, it must constantly be borne in mind that the interference with these prevailing wind directions under temporary cyclonic and anticyclonic control is both important and frequent, especially in winter and over the northern tier of states.

January Winds. The winds of winter are markedly under the control of a seasonal pressure distribution peculiar to North America. This is less fixed, less clearly defined, more complex

than that of Eurasia. Hence the winter wind systems are also less emphatic. There is here no great dominating winter anticyclone. Generalizing broadly and summarizing very briefly, the tropical high pressure belt over the adjacent oceans expands over the North American continent into a ridge of high pressure (30.20 inches), lying between the well-marked low pressure areas of the northern North Atlantic and northern North Pacific.[1] In response to this midwinter pressure distribution certain large and fairly easily recognizable wind systems are developed. Taken as a whole, the centrifugal tendency characteristic of continents during their winter season is at once apparent.

In the Eastern Province northwesterly offshore winds generally prevail along the northern and middle Atlantic seaboard. These northwesterly winds increase in velocity and in frequency to the north, into New England, and still more so in northeastern Canada, where the North Atlantic low pressure system exerts a more marked control. They become less

[1] Alexander Buchan, "Report on Atmospheric Circulation. Vol. II, Physics and Chemistry," Part V, *Report on the Scientific Results of the Voyage of H. M. S. "Challenger,"* 1889. The monthly and annual pressure charts are reproduced in Bartholomew's *Atlas of Meteorology,* 1899, Plates 11 and 12, text pages 13–14. See also F. H. Bigelow, "Report on the Barometry of the United States, Canada and the West Indies," *Report of the Chief of the Weather Bureau for 1900–1901,* Part II, 1902 (monthly and annual isobaric charts, following page 638).

Reference may be made to the following official publications on the winds of the United States: Charts showing Average Velocity and Direction of the Wind, prepared from Observations for Seventeen Years, *U. S. Signal Service,* 1891. (These charts show (1) the average velocity of the wind at sixty-five representative stations at the hours ending at 8 A. M. and 8 P. M., 75th-meridian time, respectively; (2) the prevailing direction of the wind at a number of stations east of the Rocky Mountains; (3) the highest and lowest average hourly velocity of the wind, with the hour of occurrence; (4) the average number of times a velocity of twenty-five miles or more has been observed at the principal lake stations.) *Report of the Chief of the Weather Bureau for 1896–1897* (1897), pp. 277–278 (Charts I and III show prevailing winds for January and July, based on nineteen years of observations). F. H. Bigelow, "The Average Monthly Vectors of the General Circulation in the United States," *M. W. R.,* Vol. 32 (1904), pp. 260–263. H. H. C. Dunwoody, "Summary of International Meteorological Observations," *U. S. Weather Bur. Bull. A,* 1893 (monthly charts of temperature, pressure, and prevailing winds). A. J. Henry, "Climatology of the United States," *U. S. Weather Bur. Bull. Q* (1906), pp. 67–75 (on winds). Sunshine and Wind section, *Atlas of American Agriculture* (Figs. 108 and 109 show the prevailing directions of the surface winds for January and July as observed at one hundred and seventy-five regular Weather Bureau stations).

marked toward the south, where there is an increasing tendency toward westerly and southwesterly directions and, especially on the coast of the southern Atlantic states, even toward northeasterly and northerly directions. The severe winters of the middle and north Atlantic coast states are due to these offshore winds. They come from the cold northern interior. They cause discomfort and often much suffering among those who are unable to secure proper protection in the way of clothing, heat, and adequate food. But these same cold winds insure the ice supply from northern lakes and ponds and rivers, so indispensable during the hot summers. They also very greatly increase the need of fuel for heating purposes, and thus enormously stimulate the coal industry, with its resulting demand for labor and for railroad and steamship transportation.

The influence of the Atlantic Ocean is felt when the winds blow onshore under the control of some passing high pressure or low pressure system. These easterly winds temporarily interrupt the prevailing offshore movement of the air. They bring chilling northeast snowstorms, and warmer, often rainy, southeasterly and southerly storm winds. Such interruptions of the offshore tendency are frequent in the eastern United States, where the storm control is marked. Winter winds and weather are hence very changeable. In eastern Asia, on the other hand, where the general seasonal pressure control over the winds is more emphatic and where the storm control is relatively less important, the northwesterly winds remain in much less disturbed possession. There the latter are indeed so marked that they deserve the name of winter monsoons. Eastern Asia for this reason has drier and less cloudy winters than those which characterize the Atlantic seaboard of the United States.

A comparison with Europe also naturally suggests itself. While the Atlantic coast of the United States is having its severe winters, western and especially northwestern Europe are kept abnormally mild and temperate because their prevailing southwesterly winds are blowing from the warm Atlantic Ocean and from more southern latitudes. Thus the eastern and western sides of the North Atlantic inevitably differ

greatly in climate. Northwestern Europe is to be compared with the northern Pacific coast of the United States and with British Columbia, not with the Atlantic coast. Europe is singularly favored in its exposure to these warm winter winds.

For the sake of clearness and simplicity in dealing with the prevailing winds, the Eastern Province may be subdivided into (1) Ohio valley and lower Lakes and (2) Mississippi Valley west. Prevailing southwesterly and westerly winds characterize the former of these two divisions; northwesterly and northerly winds prevail over the latter. The northern portion of the upper Lakes shares in the wind system of the latter district.[1] In the states bordering on the Gulf of Mexico, Florida has prevailingly northeast winds, whereas northerly directions predominate along the northern and western shores of the Gulf. There is also a considerable southerly (southeast) component in the western Gulf coast section, although this is not shown on the map (Fig. 53). All across the broad expanse of the Great Plains, and even into the western plains of Canada, the great northerly and northwesterly sweep of winds, noted as characteristic of the states just west of the Mississippi River, continues as a dominant climatic feature. Over the northernmost section, and across the Canadian border, a tendency toward gentler wind movement, with many calms, is observable.

It is difficult to generalize the winds in the Plateau Province. Here the inclosing mountain barriers and the broken topography greatly interfere with a free sweep of the winds. Over the southern plateau, blowing out from the continent, northerly wind directions are frequent, while under the control of the general pressure distribution southwesterly winds are most common farther north. Shut off by the high barrier of its eastern mountains, the Pacific Province has its own wind system, prevailingly from the southwest and west along shore. These winds are chiefly under the control of the marked low pressure area of the North Pacific, but the tropical high

[1] A. J. Henry, "The Winds of the Lake Region," *M. W. R.*, Vol. 35 (1907), pp. 516–520. See also E. R. Miller, "The Meteorological Influences of Lakes," *Proc. 2d Pan-Amer. Sci. Congr., Washington, U. S. A., December 27, 1915, to January 8, 1916*, Sect. II, Vol. II (1917), pp. 189–198. This paper contains numerous maps and diagrams.

pressure belt, lying farther south, also influences the wind directions, especially along the southern portion of the coast. In the interior, notably in California, wind directions are greatly modified by topography. It is to its prevailing westerly winds, coming directly from a conservative ocean, that the Pacific slope owes the far-famed mildness and equability of its winters. Warm winds blow there most of the time in the cold season, while on the Atlantic seaboard, it will be recalled, the prevailing winter winds (northwest) are the coldest that can blow. Hence the latter province has notably severe winters, especially in northern sections. The passage of winter storms, chiefly over the northern Pacific coast, or the presence of a high pressure area to the east or northeast, brings temporary easterly winds in Washington, Oregon, and California.[1] On the Pacific slope northeast winds in winter come from a cold land and bring low temperatures; on the Atlantic coast they are damp and usually bring rain or snow.

The following table gives a compact summary of the generalized prevailing winds of the United States in winter (January). All details are disregarded. Only the broadest features of the wind systems are indicated.

Compact Summary of the Prevailing Winds of Winter

Eastern Province

1. Atlantic coast: northwest, west
2. Ohio valley and lower Lakes: southwest, west
3. Mississippi Valley west: northwest, north

Gulf Province

1. Eastern (Florida): northeast
2. Central: north, northeast
3. Western (Texas): north, northeast, southeast

[1] Three types of east winds on the north Pacific coast have been distinguished by E. L. Wells, "East Winds on the North Pacific Coast," *M. W. R.*, Vol. 51 (1923), pp. 522–525. "All three are anticyclonic, depending on the existence of a high pressure area somewhere over the northern Rocky Mountain region. They are the hot, dry wind of summer; the cold, dry wind of winter, which may be followed by rain or snow; and the cold, wet wind of winter, which may be accompanied by rain, sleet, or glaze."

Plains Province

Northwest, north

Plateau Province

1. Northern: southwest
2. Southern: north, northwest

Pacific Province

1. Northern: southwest, west
2. Southern: west, northwest

July Winds. Wind maps are misleading if they are thought of as representing anything fixed or settled. The conditions of which they show a temporary phase are in a more or less constant state of transition. The prevailing winds are great sweeping currents under the control of seasonally changing pressure distribution. The winds for January and July are chosen for discussion because these are the midwinter and midsummer months, and their winds are fairly characteristic of these two seasons. But all the year through a gradual shift is taking place, from the conditions of one month to those of the next. January and July are only temporary stages on the way. We wholly fail to appreciate what these seasonal and monthly changes mean unless we can imagine the winds in this constant state of transition.

Continental and marine pressure conditions different from those of winter have a marked effect in controlling the general flow of the summer winds. A low pressure trough (29.75 inches at the center) extends across western North America, roughly from north to south, merging on the south with an east-and-west belt of low pressure over Central America and northern South America. The North Atlantic high pressure belt overlaps the continent in the southeast, and the Pacific high pressure area, with crowded isobars on its eastern side, encroaches on the land along the Pacific coast. The two ocean high pressure systems, which form part of the so-called tropical high pressure belt, are thus separated by the continental trough of low pressure. From the cooler oceans onto the warmer land the winds tend to blow centripetally, guided by these seasonal

pressures, the unchanging topography, and the temporary storm control (Fig. 54). From midwinter to midsummer, taking place gradually, as winter merges into spring and spring later merges into summer, there is a great swing of the winds over the eastern United States from the prevailing northerly and northwesterly directions of January to a prevailing southwesterly and southerly direction in July. Southerly winds gradually

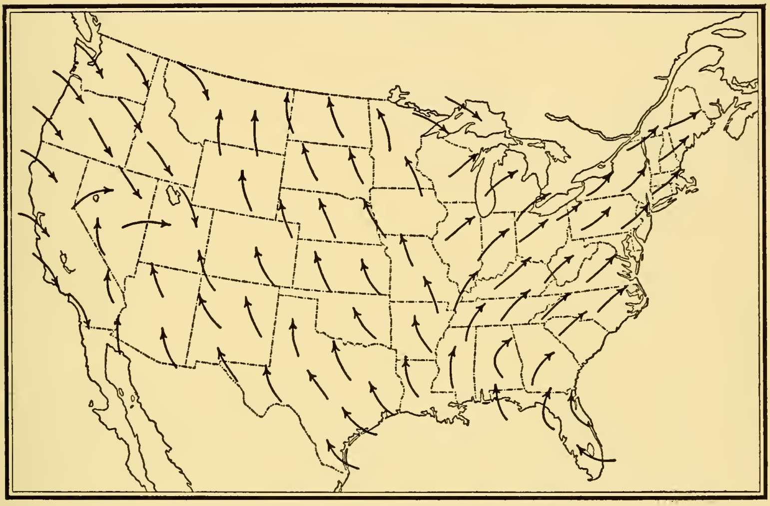

FIG. 54. Prevailing Winds in July

advance northward and eastward from the Gulf of Mexico as spring comes on, until by early summer they prevail, as southerly or southwesterly winds, over practically the whole of the United States east of the Rocky Mountains. In July the Atlantic coast and most of the Ohio valley and lower Lakes district have prevailing southwesterly winds, under the combined control of the North Atlantic high pressure and low pressure systems. This seasonal change in direction is most marked along the Atlantic slope. In the Ohio valley and lower Lakes district the prevailing wind directions are essentially the same in summer and in winter, the general pressure gradient being in about the same direction throughout the

year. Supan has shown the seasonal wind changes along the Atlantic coast by means of the following table.[1] The minus (−) sign indicates a decrease in that particular wind direction from winter to summer. In the northern section the change is mostly between northwesterly and southwesterly; in the southern, mostly between north and south. Hence it is more marked, that is, it covers a larger number of degrees, in the south.

CHANGES IN WIND FREQUENCY (PER CENT) FROM WINTER TO SUMMER (SUPAN)

DISTRICT	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.
Northeastern coast	−5	−2	1	4	7	14	−3	−16
Middle Atlantic coast	−2	−3	0	6	8	7	−2	−14
South Atlantic coast	−7	−4	3	8	7	4	−1	−9
Northern Gulf coast	−10	−6	0	3	5	9	3	−5

Hann has summarized the directions of the winter and summer winds (in percentages) on the eastern coast of North America, in middle latitudes, as follows:[2]

FREQUENCY OF WIND DIRECTIONS (PER CENT) IN MIDDLE LATITUDES ON THE EASTERN COAST OF NORTH AMERICA (HANN)

	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.	RESULTANT
Winter	11	15	6	6	7	18	14	23	N. 58° W.
Summer	8	12	6	11	13	28	9	13	S. 45° W.
Difference	3	3	0	−5	−6	−10	5	10	

The dominance of the winter northwest winds and of the summer southwest winds is clearly seen here. With the seasonal change from summer to autumn, and then to winter, the northwesterly winds advance from the continental interior toward the south and east until they, in their turn, dominate the region of the Plains, the Mississippi Valley west, and much of the Atlantic coast.

The Gulf states are crossed by what may perhaps be called a branch of the northeast trades which, under the control of

[1] J. Hann, "Handbuch der Klimatologie" (3d ed.), 1908, Vol. 3, p. 396.
[2] Ibid., Vol. 1, p. 166.

the Atlantic high pressure area and of the lower pressure over the continent, become southerly or southeasterly winds. The Plains Province is crossed by a great sweep of southerly and southeasterly winds, which extend north even across the Canadian line. Henry has pointed out that in late spring the southerly winds of the Mississippi Valley apparently divide over the Great Lakes into two branches, one forming part of the summer southerly and southeasterly winds of the Missouri valley and the Plains, the other forming part of the southwesterly winds of the Ohio valley system.[1]

This great body of moist southerly air, after crossing a wide expanse of warm Gulf and Atlantic waters, blows inland over the eastern United States around the western margin of the North Atlantic high pressure area. To it most of the warm-season rains and thundershowers are due. Without these the important staple crops east of the Rocky Mountains would never reach maturity. To these same winds, coming from warm southern latitudes, the hot eastern summers are also chiefly due. Except when temporarily interrupted by easterly winds from the ocean or by northwesterly winds from higher and cooler latitudes, they assure a preponderance of high temperatures. The tempering influence of the Atlantic has little opportunity to make itself felt. These warm southerly summer winds bring sunstroke weather, epidemics of cholera infantum, spells of suffering in the crowded cities. The development of summer resorts in the North, among the mountains, and on the seacoast, is in no small degree due to these same warm winds. Sea bathing and electric fans, thin clothing and cooling beverages, find much of the explanation of their use and enjoyment in the fact that the dominant winds of the eastern summers are the warmest winds which can blow there. In recent years economic consequences of no small importance have been attributable to these same southerly winds. In New England the brown-tailed moth, a pest which had already done great damage to fruit and other trees in Massachusetts, was spread northward and eastward over the adjoining states

[1] A. J. Henry, "The Winds of the Lake Region," *M. W. R.*, Vol. 35 (1907), pp. 516–520.

by the southwesterly winds. In Texas and the other cotton-growing states north of the Gulf of Mexico the cotton-boll weevil, another pest of serious economic importance, has been spread northward by the prevailing southerly (southeast, south, and southwest) winds of that region.

A comparison with Europe is interesting. Western and northwestern Europe have their prevailing summer winds from a cool ocean and a higher latitude. On the Atlantic coast of the United States the prevailing summer winds are from a warm land and a lower latitude. Hence in Europe the tempering influence of the conservative Atlantic largely counteracts the warming influence of the land, while along the eastern seaboard of the United States the land influence predominates.

Over the Plateau Province the winds of summer show a tendency toward northerly and northwesterly directions in the north; in the south, southerly directions prevail. As in winter, however, the inclosing mountain barriers of this region, and the local topography, greatly interfere with the development of broad, sweeping wind systems. Local mountain and valley winds, their direction determined by the immediate topography, are characteristic phenomena. They often exercise an important control over the conditions of frost occurrence.

Supan has summarized the changes in wind direction from winter to summer for certain districts west of the Mississippi River in the following table[1] (the minus (—) sign indicates a decrease in that particular wind direction from winter to summer):

Changes in Wind Frequency (Per Cent) from Winter to Summer (Supan)

District	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.
Upper Mississippi valley	−2	1	2	3	4	3	−3	−8
Upper Missouri valley	−11	2	7	9	11	1	−8	−10
Arkansas and Red rivers and Texas	−15	−4	5	21	11	−1	−5	−12
Lower Colorado River	−28	−6	2	14	26	6	−2	−11

[1] J. Hann, "Handbuch der Klimatologie" (3d ed.), 1908, Vol. 3, p. 396.

The decrease in the northerly directions and the increase in the southerly directions from winter to summer are striking, especially in the case of the last-named district, where the change is almost monsoonal in character. The annual reversal of the wind system at Yuma, Arizona, is shown in the following table:[1]

Relative Frequency of the Winds (expressed in Percentages) at Yuma, Arizona, as deduced from Tri-daily Observations 1876–1888

January	N. 28	N.E. 19	N.W. 14
July	S. 23	S.E. 21	S.W. 19

On the Pacific slope the summer winds are westerly, as in winter, but the northerly component is more marked in the warm season, the southerly in the cold. The prevailing northwesterly winds of summer are so regular, especially toward the north (for example, Oregon), that they are often locally known as "trade winds." The change from winter to summer is due to the combined influence of the warm continent and of the more northerly summer position of the Pacific high pressure system. From winter to summer there is a loss in northeast, east, and southeast winds, and a gain in west and northwest winds. This is in part attributable to the frequent cyclonic and anticyclonic winds from easterly points during the winter season. The coast mountains tend to deflect the winds along the shore. Through the Golden Gate at San Francisco the winds blow into the hot valley of California and are there turned north and south. The southerly winds of summer are a marked climatic feature of the Sacramento valley. They serve somewhat to moderate the heat of that well-inclosed and easily warmed district, and they are so steady that boatmen on the Sacramento River can count on them for sailing upstream.

The prevailing summer winds along the Pacific coast are dry because, blowing out on the eastern side of the North Pacific anticyclone, they have had no opportunity to take up much

[1] *Report of the Chief of the Weather Bureau for 1896–1897* (1897), p. 278.

moisture and, furthermore, are advancing into lower latitudes and therefore warming. The contrast between the prevailing damp and warm summer winds on the western side of the North Atlantic high pressure system and the drier and cooler winds on the eastern side of the North Pacific high pressure system is striking and, climatically, very significant. It is also significant that the prevailing summer winds on the Pacific coast come from a cool ocean and higher latitudes, just as is the case, already noted, in northwestern Europe. In the United States, however, the western mountains practically limit the moderating influence of the westerly winds to a comparatively narrow belt between the Sierra Nevada-Cascade barrier and the Pacific Ocean, and the transition from the more moderate conditions of the immediate seacoast to the more extreme climates of the interior is rapid and sharp. In Europe, on the other hand, there is a very gradual transition from the marine climates of the outermost western coastal strip to the more severe continental conditions of Russia. Again, in Europe there are very uniform climatic conditions over all the Mediterranean region, from Portugal and southern Spain across Italy and Greece, and even into Asia Minor. Civilization in the Old World was therefore able to spread westward from the Orient over a large area of remarkable climatic uniformity In North America a similar Mediterranean climate is found only over a relatively narrow zone, essentially in central and southern California. The smaller area of the sub-tropical belt of Mediterranean climates in North America than in Europe was clearly explained by Blodget.[1] "If the Gulf of Mexico were similar in position to the Gulf of California, yet extended inland like the Mediterranean, the districts of the various local peculiarities now bordering on the Mediterranean would be reproduced. . . . The space where we may look for phenomena correspondent to those of the Mediterranean is here relatively small."

The prevailing winds of summer, broadly generalized, may be briefly summarized as follows:

[1] Lorin Blodget, loc. cit., p. 241.

Compact Summary of the Prevailing Winds of Summer

Eastern Province

1. Atlantic coast: southwest, west
2. Ohio valley and lower Lakes: southwest
3. Mississippi Valley west: southeast, east

Gulf Province

South, southeast

Plains Province

South, southeast

Plateau Province

1. Northern: northwest
2. Southern: south

Pacific Province

Northwest, west

Monsoons. Monsoons, in the Indian sense of great seasonally inflowing and outflowing winds, strongly contrasted in direction and in characteristics, and markedly controlling the life and activities of all the people, are not found in the United States. Yet that a distinct monsoonal tendency exists over a large section of the country was clearly noted at least as far back as the time of Blodget, who wrote of the winds of Texas as "something very near a monsoon."[1] Later, Coffin discussed in a general way the monsoonal tendencies in the winds.[2] And Ferrel, fifteen years later, considered the conditions which give rise to monsoons and referred to the monsoon influence on the winds of the southern United States and of the Gulf of Mexico.[3] The general swing from northerly winds in winter to southerly winds in summer over the Great Plains and eastward to the Mississippi River is especially well marked in the south (for example, Texas). Here, as pointed out by Hann, the seasonal variation of relative humidity is most analogous to that of southern and eastern Asia. The weaker general pressure con-

[1] Lorin Blodget, loc. cit., p. 364.

[2] J. H. Coffin, "Winds of the Globe," *Smithson. Contr. to Knowl.*, Vol. 20, 1875.

[3] W. Ferrel, "A Popular Treatise on the Winds," p. 218.

trols and the frequent cyclonic interruptions of these seasonal winds in the United States prevent any such marked development as that attained by the monsoons of India. These Texas monsoons were studied by Harrington, who also used the name monsoons for the seasonally changing winds on the Pacific coast south of San Francisco.[1] The northerly (winter) monsoons first appear distinctly in December. While having generally a higher velocity than those of the summer, they do not maintain themselves under unfavorable conditions. They are not infrequently strengthened, under temporary conditions of rapid pressure change, into a northerly gale of high velocity known as the norther.[2] This wind is one of the marked characteristics of Texas climate, even far out onto the western Texas plains. At times northers reach as far south as Guatemala and Honduras, cross Tehuantepec, and are reported by ships in that portion of the Pacific Ocean. In midsummer a territory about five hundred miles wide and about one thousand miles long, reaching as far as the Canadian boundary, is under the general control of the southerly (summer) monsoons. These are weaker than those of winter, and bring clear weather unless a low pressure area is approaching. East of the Mississippi and south of the Ohio there is no good evidence of them, except on the Gulf coast as far as Mobile. These southerly or southeasterly winds are welcome cooling agencies during the heat of the Texas summer, even at considerable distances from the coast of the Gulf of Mexico.

Geographical Distribution of Wind Velocities in the United States. Accurate charts of average wind velocities are difficult to draw. There have been many changes in the locations and in the exposure of anemometers. Especially has this been true in large cities, where the increasing heights of skyscrapers have made the placing of these instruments on the lower buildings less and less desirable. As the anemometers have been exposed on the tops of higher and higher buildings, the recorded wind

[1] M. W. Harrington, "The Texan Monsoons," *Bull. Phil. Soc. Wash.*, Vol. 12 (1894), pp. 293–307; *Amer. Met. Journ.*, Vol. 11 (1895–1896), pp. 41–54; A. J. Henry, "The So-called Monsoonal Winds of Texas," *M. W. R.*, Vol. 52 (1924), pp. 304–305.

[2] See Chapter XVI.

velocities have become greater and greater. Fig. 55 shows the average hourly wind velocity as determined by Day.[1] The figures indicate the velocity estimated for the uniform elevation of a hundred feet. A correction has been applied to allow for the retardation of the winds by the buildings of large cities.

In the Eastern Province, stations close along the Atlantic coast and on the Great Lakes have the most wind. The line

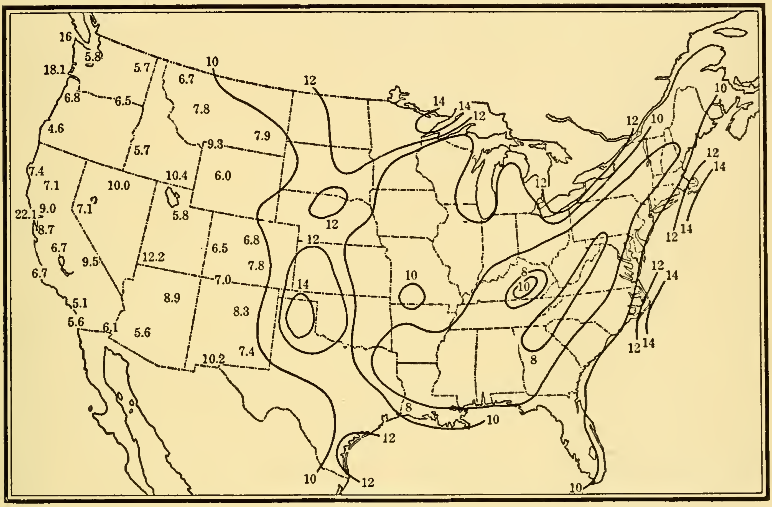

FIG. 55. Hourly Wind Velocity (elevation 100 feet)

of ten miles an hour closely parallels the margins of these bodies of water. Somewhat higher winds (ten to fourteen miles an hour) prevail at the most exposed points on the Atlantic seaboard; for example, at Cape Cod, Massachusetts, and Cape Hatteras, North Carolina, and also to the leeward of Lakes Erie and Ontario. In the Gulf Province many coast stations have about the same wind movement as that of the Atlantic

[1] P. C. Day, "The Winds of the United States and their Economic Uses," *Yearbook U. S. Dept. of Agric. for 1911* (1912), pp. 337–350, Plate XXIII. Fig. 106 in the Sunshine and Wind section of the *Atlas of American Agriculture* is Day's map modified by substituting lines of equal wind velocity for the numerical data in the region west of the Rocky Mountains. Fig. 55 herewith is redrawn from Day's Plate XXIII. See also P. C. Day, "Important Winds of the United States from an Insurance Standpoint," *Insurance Age*, Vol. 50 (1921), pp. 201–203.

and Great Lakes stations. The small amount of friction over water and exposure to frequent storm winds account for these high velocities. Lashed by winter gales and autumn hurricanes, the waters off Cape Hatteras are proverbially rough. It is but natural that such meteorological handicaps to navigation should have led to the digging of the Cape Cod Canal, completed in 1914, and to the project of constructing a protected waterway for vessels among the islands and across the lagoons and bays along the Atlantic coast farther south. The popular designation of "windy city," often confined to Chicago, applies with equal truth to other stations on the Great Lakes and the Atlantic coast.

Over the interior, away from large bodies of water; among the mountains; in forests and in sheltered valleys, lower wind velocities are the rule. Exposed mountain tops, like Mt. Washington, New Hampshire (about 6300 feet), are much windier. The Mt. Washington records have shown velocities averaging over twenty-five miles an hour in summer and over thirty miles in winter. Mt. Weather, Virginia (1700 feet), and Mt. Mitchell, North Carolina (6700 feet), have much less wind because they are farther away from the northern storm paths.

Very striking is the broad zone of the Great Plains, with wind velocities closely resembling those along the eastern seaboard and the Great Lakes—winds which are ocean-like in character, as vast stretches of the Plains are themselves ocean-like in their monotony and in their unbroken sweep to the far-away horizon. No more striking illustration of the wind velocities on the Great Plains has ever been given than Captain Lewis's description of the occasion, on the famous Lewis and Clark expedition, when one of his boats, which was being transported on wheels, was blown along by the wind, the boat's sails being set! Surely this story emphasizes the analogy between the winds of the ocean and the winds of the Plains. Over this great treeless open country, but little retarded by friction, blow winds of remarkable uniformity and of relatively high velocity, averaging ten to twelve miles an hour, and even reaching fourteen or fifteen miles in the region

of the Texas "Panhandle." Pikes Peak (14,134 feet), although more than twice as high as Mt. Washington, has much less wind than the New Hampshire summit, because it is in a region of much less marked cyclonic control. The average velocities are 22 miles an hour for the year; 27.1 in March; 13.5 in July.

It is a climatic fact of great economic importance that the wind velocities over the Great Plains are so extraordinarily well adapted for driving windmills. The configuration of the continent and the distance from primary sources of moisture supply result in giving this great interior region a somewhat deficient rainfall. It is a district over most of which general farming without irrigation is a hazardous undertaking. To secure water for irrigating, for stock, and for domestic use, recourse must be had chiefly to underground supplies. This necessitates pumping; and in the wind conditions of these very same Plains—in the relatively high and steady wind velocity—there is a source of power which is economical and reliable. Hence the windmill is one of the most characteristic features of the Great Plains. Far away in the distance, long before the farm buildings themselves can be seen, the tall steel frame, with its revolving wheel at the top, stands out against the distant sky-line. There is here a curious and interesting climatic compensation of inestimable money value to the farmers of the western Plains. In other parts of the country also, where there is no constant necessity of irrigation and where the winds, although less favorable as a source of power, are nevertheless reasonably well adapted for driving windmills much of the time, there should be an increasing use of this cheap and effective source of power for pumping water to be used temporarily in times of drought.[1]

[1] As illustrations of the work done by windmills, the following cases reported by Waldo may be cited (Frank Waldo, "Wind as a Motive Power in the United States," *Rev. of Rev.* (New York), Vol. 12 (1895), pp. 299–302): A wheel 12 feet in diameter raised from 50,000 to 100,000 gallons of water a month to a height of 50 feet (Texas). A 10-foot wheel in Wisconsin raised 50 barrels of water daily to a height of 50 feet. A 10-foot wheel in Iowa raised enough water to a height of 40 feet to supply 300 head of cattle. In Missouri a 16-foot wheel ground 20 bushels of corn in an hour. In Nebraska a 10-foot wheel raised 1000 gallons of water daily to a height of 70 feet.

So widely varying under the influence of local topography are the wind velocities over the Plateau Province, and so few and scattering are the available data, that lines of equal wind velocities cannot well be drawn for that section. The chart shows velocities varying from five to six miles an hour to from ten to twelve miles. It is to be expected that in such a broken and mountainous topography the velocities will on the whole be distinctly smaller than those on the Great Plains. The most sheltered localities are generally the least windy. Yet the use of windmills is by no means impossible in many parts of the Plateau Province, and the judicious choice of windmill sites where the conditions are most favorable would provide many localities with the means of irrigating.

In spite of its name the Pacific coast at its northern exposed stations has higher average wind velocities (sixteen to twenty-two miles an hour) than those at exposed points on the Atlantic coast. The conditions on these two coasts are different, however, and cannot be directly compared. The higher velocities along the Pacific seaboard have been recorded on bluffs several hundred feet in elevation. South of San Francisco light winds prevail, for storm control becomes less and less marked southward along the coast, and the pressure gradients are weaker.

Maximum Wind Velocities. The most violent winds with which man has to contend in the United States are those of the tornado. Considering the size of the country, tornado blasts are relatively rare. They are in general limited to the tornado belt of the eastern United States; that is, to the central and southern Mississippi Valley region, and from there, with decreasing frequency, to the states lying to the west and east. The sudden squall winds which accompany severe thunderstorms are responsible, next after tornadoes, for the highest winds of interior districts. In many forests, often far from the beaten track of man's present-day wanderings, records of former tornadoes and of other high winds are preserved, decades after the occurrence of the blasts which uprooted and broke off the trees. "Fossil" tornadoes may be distinguished by the tangle and criss-crossing of the trees which give the evidence of the tornado whirl. A straight "slash" through the forest, with

the trees all prostrate in the same direction, is the "fossil" record of a straight-line gale or of a thundersquall.

West Indian hurricanes are responsible for the maximum wind velocities which are recorded along the south Atlantic and Gulf coasts; severe winter storms bring the highest winds at the stations along the margin of the north Atlantic, north Pacific, and Great Lakes.

For engineers and for architects it is important to know the absolute maximum of wind velocity which may occur in any district. But for ordinary purposes, and as a matter of popular interest, a much more general indication of the highest wind velocities amply suffices. Excluding the relatively rare tornado, winds blowing for short periods at the rate of from fifty to seventy-five miles an hour may occasionally be expected at interior (lowland) stations, while velocities of from seventy-five to eighty or ninety miles are not unlikely to occur in the most severe gales along the coasts. Winter gales and summer and autumn hurricane winds along the Atlantic seaboard too often bring danger and disaster to shipping. The storm warnings of the Weather Bureau, indicating gales dangerous to navigation, are seen by mariners with discouraging frequency.

In the western mountain regions the highest winds accompany the more severe winter storms and have an important economic bearing in that they drift and pack the snow in the mountains, consolidating it for subsequent slow melting in spring and summer and thus providing a uniform and continuous supply of water for irrigation. Taking the country as a whole, the lowest wind velocities are found in the southwestern interior.

During the passage of severe winter storms exposed stations on the Pacific coast from San Francisco northward are subject to gales with velocities running up to from fifty to ninety miles an hour or even over one hundred miles.[1] The wind directions in these Pacific coast gales are southeasterly or

[1] A. G. McAdie and W. W. Thomas, "Some High Wind Records on the Pacific Coast," *M. W. R.*, Vol. 31 (1903), pp. 64–68. For a discussion on forecasting high winds in different parts of the United States see "Weather Forecasting in the United States," *U. S. Weather Bur. No. 583* (1916), pp. 217–252. A considerable number of type weather maps accompany this discussion.

northwesterly. Shipping is liable to suffer damage; inland the loss, if any, is chiefly confined to the uprooting of standing timber. To the south the maximum velocities are much lower, the highest winds blowing when winter storms move southward along the coast or in connection with low pressure areas over the interior. Occasionally, even in central and southern California, strong winds may damage standing crops.

Seasonal and Diurnal Variation in Wind Velocity. With the annual progress of the seasons there comes a seasonal variation in wind velocities. For the country as a whole, spring (March, April) is in general the windiest time of the year, middle and late summer (July, August) the calmest. March is proverbially a windy month. In the long run it deserves its reputation.[1] It is a transition month. The combined influence of the still active winter storm control and the rapidly increasing diurnal (solar) control of summer makes for active wind movement. The difference between the average wind movement in the windiest and calmest months varies between 30 and 70 per cent in different sections. The least difference is found over the Plains, the upper Lakes, and the south Atlantic coast; the greatest, on the north Pacific coast. It is a fact of notable economic importance that there is comparatively little seasonal difference in the wind velocities over the Great Plains. It is also economically important that the highest winds which sweep over the Plains are most common in winter and spring, when the contrasts in temperature are most marked, and not in summer. The damage to crops from this source is thus minimized.

The general increase in wind velocity from a minimum in the early morning to a maximum at 2 or 3 P.M. is a characteristic feature over most of the country, although there are exceptions, as on the Pacific coast. The change is most marked at inland stations, on clear days, and in summer, when storm control is least marked. Day has charted the average hourly wind velocities for the daylight hours (6 A.M. to 6 P.M.), for the approximate hour of maximum wind movement (3 P.M.), and for

[1] W. B. Stockman, "March and Winter Winds," *M. W. R.*, Vol. 31 (1903), pp. 223–225.

the approximate hour of least wind movement (6 A.M.).[1] The daytime increase in wind velocity near the earth's surface over that of night-time averages from 20 to 40 per cent, and may reach 50 per cent or more. This increase is most marked in the arid portions of the country. The average daylight velocities approximate ten miles or more an hour over much of the United States. The Great Plains are conspicuous on account of their high velocities (over twelve; in the Texas Panhandle, over sixteen), which are about the same as those at exposed points along the Atlantic coast and on the Great Lakes. Comparing the extreme day and night velocities (that is, the average velocities at 6 A.M. and 3 P.M.), the increase in the afternoon velocity over that of early morning is seen to be most marked in regions of light winds, as in protected valleys of the Rocky and Appalachian mountains (75–100 per cent). Over the Great Plains this increase is less (30–50 per cent). The Plains, then, stand out conspicuously in their wind conditions. They have relatively high average wind velocities, there is little seasonal variation in velocity, and the winds of night-time are relatively higher, as compared with those of daytime, than is the case over much of the country. All this makes the winds of the Great Plains an important and reliable source of power.

[1] See footnote 1 on page 155; Fig. 107 in the Sunshine and Wind section of the *Atlas of American Agriculture* shows the average velocity of the wind at 3 P.M. for the year (in miles per hour); Fig. 110 shows the diurnal march of wind velocity at Dodge City, Kansas.

For earlier publications see F. Waldo, "Daily March of the Wind Velocities in the United States," *Amer. Journ. Sci.*, 3d Ser., Vol. 49 (1895), pp. 431–442; "The Geographical Distribution of the Maximum and Minimum Hourly Wind Velocities, and their Relations to the Average Daily Wind Velocities for January and July, for the United States," *Amer. Met. Journ.*, Vol. 12 (1895), pp. 75–89; "Synchronous or Simultaneous Geographical Distribution of Hourly Wind Velocities in the United States," ibid., pp. 145–151; "The Relations of the Diurnal Rise and Fall of the Wind in the United States," *Amer. Journ. Sci.*, 3d Ser., Vol. 50 (1895), pp. 235–238.

CHAPTER VIII

MEAN ANNUAL RAINFALL

RAINFALL MAPS IN GENERAL · RAINFALL OF THE EASTERN AND GULF PROVINCES · RAINFALL OF THE PLAINS · RAINFALL OF THE PLATEAU PROVINCE · RAINFALL OF THE PACIFIC COAST · RAINY WINDS

Rainfall Maps in General. There are difficulties in the study of the rainfall distribution over as large an area as that of the United States. Not only do the charted amounts of precipitation vary greatly in different sections, but there is still, and will be for years to come, some uncertainty as to just how much rain and snow actually fall. This is especially true of the western plateau and mountain country. Here rain-gauges are generally widely scattered and are mostly at relatively low levels, so that but little can be definitely known regarding the precipitation on the mountains. These difficulties are by no means confined to the West. Even in thickly settled areas rain-gauge readings are known to be unsatisfactory. The local conditions of exposure, of altitude, and of topography have so marked an influence on the catch of the individual gauge that the whole matter of actual rainfall distribution is in much doubt.

Rainfall maps for the United States are numerous. They differ considerably from one another. Some authorities have limited themselves rigidly or almost rigidly to the observed readings of rain-gauges. Others have based their maps on actual observations so far as these go, but have also made use of all known facts regarding topography, stream-flow, wind direction, vegetation, and other conditions in making reasonable inferences as to the amounts of precipitation over the higher mountain slopes and summits and over unoccupied areas in general.[1]

[1] "Rainfall and Charts of Rainfall," *M. W. R.*, Vol. 30 (1902), pp. 205–243 (presents the views of a large number of meteorologists, geographers, botanists, and others); W. G. Reed and J. B. Kincer, "The Preparation of Precipitation

What may be termed the more strictly meteorological group have, in general, taken the position that rainfall charts should show only such amounts of precipitation as have been actually measured. They have held that inferences regarding precipitation over areas where no records are available necessarily largely reflect only the individual opinion of the author, and lose greatly in value on that account. They maintain that when inferred isohyetal lines are drawn over regions where there are but few stations that fact should be very clearly indicated, a distinction being made between observed and inferred conditions. In the case of mountains whose rainfall is not definitely known, there is no reason why the area should not be left blank on the map. Or, if desired, the slopes for which observations are lacking may be inclosed by an isohyetal line whose position is definitely established, and the words "probably over —— inches, or millimeters," may be entered within this line. On the other hand, the second group, which is largely composed of geographers and of those who have broad geographic conditions in mind, takes the view that the relief and all other known surface features of the country should be recognized and utilized in inferring the positions of the isohyetal lines, and that many serious errors in locating these lines, such as drawing a line across a hilltop when it should obviously go around the base, may be avoided if a contour map is used. The extent to which the topography of any region should be taken into account obviously depends on the scale of the map. The smaller the scale, the fewer the details which may be shown. A rainfall map which attempts, on a reasonably sound basis of topography, water supply, and vegetation, to show the inferred amounts of precipitation over areas where gauge readings are lacking, is more satisfactory in general climatological studies than one which is based solely upon actually recorded amounts of rainfall. In any use of rainfall charts it must be remembered that the transition from one color or one kind of shading to another, which stands out

Charts," ibid., Vol. 45 (1917), pp. 233–235 (presents the principles recognized and the methods followed in preparing the accompanying new average annual rainfall chart of the United States).

so strikingly on the maps, gives an erroneous impression of a suddenness of change in the amount of rainfall on the two sides of that line. The increase or the decrease in rainfall from that indicated by one isohyetal line, or by one color or shading, to that shown by the next is gradual.

In detailed studies of rainfall, as in its relation to crops or irrigation or water power, it is usually necessary to use maps which show the amounts of precipitation for every 10 in., 5 in., or even 1 in. For more general purposes, as in a review of the larger facts of rainfall, it is simpler and generally sufficient if the distribution of certain more or less critical rainfall amounts is alone considered. This latter scheme is, for example, well adapted for use in constructing wall maps of mean annual rainfall, where the larger facts must be presented in the clearest possible way. From the point of view of man and of his relation to the mean annual rainfall it has become more or less conventional to adopt certain critical grades of rainfall. Such critical rainfall amounts are below 5 in.; 5 to 10 in.; 10 to 20 in.; 20 to 40 in.; and over 40 in. Districts of very heavy rainfalls, of 80 in. and over, may be included as a separate group. Where the rainfall is less than 5 in. a year there are true deserts. Where 5 to 10 in. fall the country is arid, agriculture requires irrigation, and the available water supply is extremely limited. Only a small portion of these areas can ever be useful to man. The districts with from 10 to 20 in. are generally called semi-arid. Roughly, they include dry-farming areas, although, as shown by L. J. Briggs and J. O. Belz, these rainfall limits are only approximate in the United States.[1]

Many factors besides the mean annual rainfall control agricultural operations: the monthly distribution of the rain; the amount of evaporation; the temperature; the methods of cultivation; the soil, etc. Dry farming is carried on, more or less successfully, over increasing portions of this semi-arid area in the United States, and there is also a considerable use of irrigation over other smaller parts of it. The development of these areas has been rapid, and there is still possibility of

[1] L. J. Briggs and J. O. Belz, "Dry Farming in Relation to Rainfall and Evaporation," *U. S. Bur. of Plant Industry Bull. 188* (1910).

great future development. Rainfalls of from 20 to 40 in. are sufficient for all ordinary agricultural or water-supply purposes. Above 40 in., and up to (say) 80 in., the amount is abundant; above 80 in. it may be described as superabundant. The use of some such grades of rainfall simplifies the description of ordinary precipitation charts and helps greatly in memorizing them.

The map of the mean annual precipitation over the United States (*Frontispiece*) embodies the best and latest information which is now available.[1] It recognizes the absolutely essential importance of using only records covering a uniform period or reduced to a uniform period. In the location of the isohyetal lines it takes reasonable account of topography and of other conditions which indicate the amount of precipitation or which control it. The records of about sixteen hundred stations for the twenty-year period from 1895 to 1914 were used, together with two thousand additional records from five to nineteen years in length, the latter series being reduced to the same period of twenty years.

Rainfall of the Eastern and Gulf Provinces. The isohyetal lines over the eastern and especially the southeastern United States show a general parallelism with the trend of the Atlantic and Gulf of Mexico coasts which is highly significant. They "head up" to these two bodies of water. They spread out from the Gulf of Mexico toward the interior. This fact, together with the distinct decrease in rainfall with latitude northward from the Gulf and the decrease with longitude westward from the Atlantic, indicates that these two sources of water vapor are essential in supplying the precipitation over this section of the country. From St. Paul, Minnesota, to New Orleans, Louisiana, the mean annual precipitation increases by nearly 30 in. The influence of the Atlantic Ocean is clearly seen along the eastern seaboard, extending inland to the Appalachians, especially over the northern sections of the coast. It is probable that the bulk of the direct supply from the Atlantic does not extend inland to any considerable extent

[1] Reproduced from *Atlas of American Agriculture*, Part II (Climate), Section A, Fig. 2.

beyond the Appalachians. From Eastport, Maine, to St. Paul, Minnesota, the decrease in mean annual rainfall is about 15 in. The Great Lakes are a subordinate and relatively unimportant source of rainfall.

The importance of the Gulf of Mexico and of the Atlantic Ocean in supplying the moisture which, owing to the western mountain barriers, is prevented from coming far inland from the Pacific cannot be overemphasized. Taken as a whole, a remarkable combination of favorable conditions exists for producing abundant and well-distributed rainfall over the eastern United States. First, the warm waters of the Gulf of Mexico —occupying latitudes which, with a different distribution of land areas, would be an American Sahara—and the Atlantic Ocean, kept at a relatively high temperature along a considerable extent of the coast by the warm Gulf Stream, are sources of a plentiful water vapor supply near at hand. Second, the prevailing winds during the most critical season of the year (summer) blow with an almost monsoon-like persistence from the warm waters of the Gulf of Mexico, at high temperatures and well laden with water vapor, far into the interior of the continent. Third, the topography of the eastern half of the country offers no serious obstacle anywhere to the free flow of these winds. Fourth, the ordinary cyclonic storms of the prevailing westerly winds play a very important part in the control of precipitation, especially in winter. At that season, when the pressures are high, the prevailing winds blow out from the continent, the continental type of climate tends to give cold, dry, and clear weather, and the numerous and well-developed cyclonic storms, with their damp easterly and southerly winds from the Atlantic and from the Gulf, bring rain or snow which, under non-cyclonic controls, would never fall. In summer the cyclonic control is weak, but there is then much less need of this source of rainfall, for the continental pressures are low, the prevailing winds are on shore and very warm, and themselves supply plenty of moisture. Nevertheless, the fewer and weaker cyclones of the warmer months intensify the southerly indraft and favor the occurrence of local showers and thunderstorms.

The rain-shadow effect of the western mountains would prove a very serious climatic handicap to the region lying to the east of the Rocky Mountains if it were not for this remarkable combination of conditions. In eastern Asia, in latitudes 30° to 40° N., there is a district climatically similar in many respects to the eastern United States in the same latitudes. Yet in Asia, owing to an absence of some of the favorable controls which are so striking in North America, the area with precipitation over 40 in. is greatly restricted. In western Europe, on the other hand, there are no high western mountains. Hence there are no such marked rain-shadow effects as in the United States. Hence, also, there is no similar need for a new moisture supply for the interior sections such as exists in the United States. The Mediterranean Sea seems analogous to the Gulf of Mexico, but the influence of the former is fairly well shut out from the interior by the mountain barrier of southern Europe. It is very fortunate for the United States that there is no transverse mountain barrier like the Alps stretching across the Mississippi Valley. In Europe the Alpine barrier is not a climatic handicap, because the moisture supply from the Mediterranean is not essential to the countries lying to the north.

The favorable rainfall conditions which prevail over the eastern United States have inevitably attracted the attention of almost all writers on the climatology of North America. Everywhere over this great area the rainfall is over 20 in.; about one half of it receives more than 40 in.; no inconsiderable portion has more than 50 in.; in restricted localities the amounts exceed 60 in. The rainfall is greatest (in general, 50 to 60 in.) over the Gulf states, with the exception of Texas, and along most of the immediate seaboard of the Carolinas and Georgia. It decreases from these amounts to from 40 to 45 in. over most of the northern and central Atlantic coast, to from 30 to 40 in. over the prairies, and to 20 in. at about the 100th meridian. In the West the isohyetal lines trend nearly north-south. The heavier rainfalls, excluding those due to topographic controls, are thus found near the bodies of water which supply the moisture. From Florida, along the eastern

and northern Gulf coasts to the southwestern corner of Louisiana, the amounts vary between 50 and 60 in. Most of Louisiana, Mississippi, and Alabama, and a good deal of southern Arkansas have over 50 in. Along the Texas coast there is a very rapid decrease from 50 in. in the northeast to from 20 to 25 in. in the extreme south, the isohyetal lines trending very nearly north and south. This Texas section is not nearly so favorably located with regard to rainfall as is the rest of the Gulf coast, both in the matter of its exposure to the prevailing damp winds blowing across the Gulf and in its relation to cyclonic storms. Along the Atlantic seaboard the amounts decrease somewhat with increasing latitude from 55 to 60 in. in extreme southeastern Florida to from 40 to 45 in. in Maine.

The influence of the Appalachian Mountains is indicated in the irregularity of many of the isohyetal lines and in the occurrence of certain local areas of heavier or lighter precipitation. As a whole, however, since the mountains are not very high, and since their trend is approximately parallel with that of many of the rain-bearing winds and with the tracks of numerous cyclones, it is not to be expected that there should be any very marked differences in rainfall on the opposite slopes. The most marked topographic control over rainfall in the Appalachians is in a small area along the southern and eastern slopes of the mountains of southwestern North Carolina, northwestern South Carolina, and northern Georgia. In this elongated area the rainfall amounts increase from 50 and 55 in. over the lower slopes to 60 in. at greater elevations, reaching 80 in. as a maximum in the mountains of the southwestern corner of North Carolina. A combination of topography and of exposure to rain-bearing winds doubtless explains this interesting peculiarity. Far away to the north the White Mountains of New Hampshire stand out as a small district of heavier precipitation (over 50 in., Mt. Washington having over 80 in.), and in New York State the position of the Adirondacks is clearly indicated by the isohyetal lines of 45 and 50 in. The higher parts of the Cumberland Plateau in Tennessee have over 55 in., and there are other less important areas with somewhat increased precipitation; for example, the mountains of

West Virginia. Noticeable also are the effects of the topography in causing somewhat diminished rainfall. The Hudson-Lake Champlain depression is clearly marked, with less than 30 in. in the north. The inner longitudinal valleys of Virginia and West Virginia stand out sharply with their 40-inch and even 35-inch isohyetal lines, a rainfall 5 to 10 in. or more below that of the surrounding mountain country. The plentiful rainfall over the Appalachian area as a whole furnishes abundant water power in numerous well-filled rivers and thus becomes an important factor in the industrial development of the eastern states. The only other striking topographic controls over rainfall in the eastern United States are seen in the deflection of the 50-inch line over the Ouachita Mountains of central Arkansas and in the local increase of rainfall from 40 to 50 in. over the Boston Mountains in the northwestern part of the same state.

The chart does not indicate any very striking influence of the Great Lakes on the mean annual precipitation in their immediate vicinity. This fact was pointed out many years ago by Blodget. In 1899 Henry wrote, "The Lakes themselves, with the possible exception of Lake Superior, do not seem to have a very marked influence on the precipitation of moisture on adjacent land areas."[1] The lee shores of the Lakes in several cases show a somewhat heavier annual rainfall, but relatively the excess is a rather small amount, generally well under 5 in. The lake effect is probably greatest in the case of Lake Superior. Local topography is here, as always, an important factor in determining the amount of rainfall. There is a rather significant widening toward the Lakes of the belt between the 30-inch and 35-inch isohyetal lines and, to a somewhat less marked degree, of that between the 35-inch and 40-inch lines. This fact, together with the general trend of the lines in the lake region, indicates that the lake influence is present, although it is not striking. It should be borne in mind that the rainy winds are to a considerable extent from easterly directions, and

[1] A. J. Henry, "Normal Precipitation in the Region of the Great Lakes," *M. W. R.*, Vol. 27 (1899), pp. 151–153. See also E. R. Miller, "The Meteorological Influences of Lakes," *Proc. 2d Pan-Amer. Sci. Congr., Washington, U. S. A., December 27, 1915, to January 8, 1916.* Sect. II: Astronomy, Meteorology, and Seismology, Vol. II, pp. 189–198.

for that reason the lack of any very decided influence of the prevailing westerlies is not surprising. In other words, the precipitation which comes with westerly winds is just about balanced by the precipitation which falls, rather less often, with easterly winds. It is to be expected that in winter, when the westerly winds blow across the open water of the Lakes, the snow will be heavier on the lee sides. It may be observed that the Great Lakes are not bountifully supplied by many large rivers, hence they are very dependent for their water supply upon local rainfall and snowfall. An interesting point regarding the Great Lakes was brought out by Blodget when he wrote that they "could not exist if extreme continental features of climate were ever fairly developed there." [1] In other words, the Lakes occupy a district which naturally has a well-marked continental climate, and unless the extremely favorable conditions for rainfall which have been explained above were present, there would be a deficiency of rainfall here. These conditions result in a modification of the continental characteristic of deficient or light rainfall: the basins of the Great Lakes are well filled, and the Lakes in their turn modify the local climates.

The bulk of the population of the United States is found in the eastern section, where the mean annual rainfall ranges between 20 and 50–60 in. Here sufficient moisture favors successful agriculture, with annual summer crops raised by ordinary farming methods. Here the rainfall is favorable, so that the agricultural provinces are based largely on temperature and therefore in general follow the latitude lines, latitude and soil being the principal crop controls.[2] It is the sufficiency of the rainfall, combined with its favorable distribution through the year, that is of such inestimable advantage to agricultural prosperity. The generally abundant spring and early summer showers, the prevailingly high summer temperatures, and the plentiful supply of atmospheric humidity combine to produce an almost semi-tropical type of summer climate very favorable, in the South, for sugar cane and for cotton and, farther north,

[1] Lorin Blodget, loc. cit. (See *M.W.R.*, Vol. 42 (1914), p. 24.)

[2] M. Smith and Others, "Graphic Summary of American Agriculture," *Yearbook U.S. Dept. Agric. for 1915* (1916), pp. 329–403.

for wheat, corn, oats, and other cereals. It has been well said that "there is no great area so far in the interior which presents a similar result."

Rainfall of the Plains. The general east-west and northeast-southwest trend of the isohyetal lines over the southern and eastern states becomes a roughly north-south trend over and somewhat to the east of the Great Plains, and continues to be the general characteristic all the way to the Pacific, with, of course, many local irregularities due to topographic controls. The isohyetal lines may be thought of as swinging on a pivot located over the western Gulf states, their eastern free ends traveling north, northwest, and west until they reach an approximately north-south position. The 20-inch line, because of its critical controls over vegetation, is often taken as the eastern boundary of the Great Plains. It lies in a general way along the 100th meridian, but is east of it in the Dakotas and west of it in the remaining states to the south. Hence, along the 100th meridian, the rainfall is between 15 and 20 in. in the north and about 25 in. in Oklahoma and most of Texas. This difference between north and south naturally points to the Gulf of Mexico as the source of the rainfall. There is, thus, over the Plains as a whole, no change of rainfall with latitude; no decrease, as there is farther east; no increase, as there is farther west. The Rocky Mountain divide roughly separates these two contrasted relations of rainfall and latitude. Over the Plains, owing to the increasing distance from the chief source of moisture, the rainfall as a whole decreases toward the west in spite of the fact that the altitude increases, falling to 10–15 in. over much of eastern Montana, Wyoming, and Colorado.

The western part of the Plains Province includes a varied topography, with mountain climates and many marked cases of topographic controls over rainfall. At a first glance the rainfall map gives the impression of complexity and confusion, but a more careful examination of its details leads to the following simple statement. The more marked (that is, the higher) topographic features are clearly local centers of heavier precipitation, but the amounts are in no case excessive (20 to 25+ in.). Several mountain groups are clearly indicated by

their heavier rainfalls. Such are the Black Hills of South Dakota; the Lewis Range and the Little Belt Mountains of Montana; the Absaroka and Wind River ranges and the Big Horn Mountains of Wyoming; the Front, Park, and Sawatch ranges and Pikes Peak in Colorado; the Sangre de Cristo Mountains of Colorado and New Mexico. The Black Hills, so named because of the dark forests which result from their heavier rainfall, are a center of lumbering in the midst of a surrounding treeless country of cattle or sheep ranges. Elsewhere, also, the increased precipitation of the greater elevations makes possible forest growth. The "parks" of Colorado, for example, have sufficient precipitation to support a growth of pines which add greatly to the natural beauty of these intermontane basins. A few districts which are topographically unfavorably situated have less than 10 in. of rainfall. Such are the Big Horn and Green River districts of Wyoming and a smaller area between the Sangre de Cristo and San Juan mountains in Colorado.

Too far from the Atlantic and the Gulf of Mexico on the one side to receive an abundant supply of moisture from those sources, and too far and too well shut off from the Pacific on the other to be able to draw upon that source, the Plains must inevitably be relatively dry. Storms cross them, it is true, especially in the north and in winter, but precipitation cannot be heavy when the inflowing winds do not carry much moisture. The somewhat more abundant rainfall of the loftier mountains is an important source of supply for the rivers whose waters are used for irrigating the lower country to the eastward. To the west of the 20-inch isohyetal line there is a vast region where agriculture of the type characteristic of the rainier East is as a whole no longer found (except on the northern Pacific coast); where water, not land, is the measure of success. Over all this great western area the agricultural provinces are determined by altitude and rainfall. They therefore extend roughly north and south, as do the mountain systems. Dry farming, grazing, irrigation, are man's three methods of making use of the land—dry farming where the rainfall is most abundant; stock-raising where there is not enough moisture even for dry farming;

irrigation over the limited areas where water is available. Once the home of immense herds of bison which pastured on the natural grasses; then browsed over by millions of cattle; afterwards, in the days of the "boom" of the later '80's and even more recently, the scene of unhappy and disastrous attempts to use them for large-scale agricultural operations of the eastern type, the natural limitations of the Great Plains have come to be fully recognized. They were never fitted to be a region of vast farms for raising crops by methods which take no account of the special climatic and soil limitation.[1] They could not continue to support vast herds of cattle which exhausted the natural pasturage. They are available, here for dry farming; there for local irrigation from streams or wells, with small individual farms and cattle ranches, each farm having its own cultivated patch of cereals and vegetables and fodder for the cattle; elsewhere, again, for grazing.

It has been pointed out by Henry that, while no hard-and-fast rule can be laid down, the line of 15 in. of rainfall per crop-growing season very broadly defines the area which is devoted to the cultivation of cereals in the United States.[2] Yet the very remarkable crops harvested in the Red River valley are produced with a less amount; and in the dry-farming wheat region about Spokane, Washington, the rainfall for April to June averages 4.5 in., which is about that of a single month in the Mississippi Valley wheat country. In discussing the relation of spring-sown wheat yield to rainfall on the Great Plains, Briggs and Belz conclude that when the rainfall for April to July, inclusive, is less than 8 in., the yield barely suffices to cover the expense of producing the crop.[3] It is significant that the heavier precipitation of the eastern United States, com-

[1] W. D. Johnson, "The High Plains and their Utilization," *Ann. Rept. U. S. Geol. Surv.*, Vol. 21, iv (1901), pp. 601–741. See also J. Warren Smith, "Rainfall of the Great Plains in Relation to Cultivation," *Annals Assoc. Amer. Geogr.*, Vol. 10 (1920), pp. 69–74; and idem, "Relation between the Annual Precipitation and the Number of Head of Stock Grazed per Square Mile," *M. W. R.*, Vol. 48 (1920), pp. 311–317.

[2] A. J. Henry, "Rainfall and Snowfall of the United States, with Annual, Seasonal, and Other Charts," *U. S. Weather Bur. Bull. D*, 1897.

[3] L. J. Briggs and J. O. Belz, "Dry Farming in Relation to Rainfall and Evaporation," *U. S. Bur. of Plant Industry Bull. 188* (1910).

bined with favorable conditions of temperature and soil, produced a great natural forest cover which the early settlers were obliged to clear away. This was a slow and laborious task and greatly delayed the progress of white settlement. In the West, on the other hand, over the treeless areas of the Great Plains, for example, there was no such obstacle. Vast stretches of the West were available for rapid occupation, for grazing, or for agriculture. The difficulty here is the impossibility of supporting a large population owing to the deficient rainfall.

Rainfall of the Plateau Province. Over the Western Plateau Province, with its varying topographic features, its rugged slopes, and its sparse population, the rainfall is still but imperfectly known. This is distinctly a rain-shadow area, of generally deficient precipitation. It is desert, arid or semi-arid, except when the higher mountains or plateaus provoke a more abundant rainfall, especially in the north, where the western mountain barrier is less effective and the storms are more numerous. The moisture which, were it not for the western mountain barriers, would come from the Pacific, falls in great part as rain or snow on the windward slopes of these mountains, on the narrow Pacific slope. Even the most superficial comparison of the topographic and rainfall maps of the Plateau Province shows at once a remarkably close correspondence between them. In many respects the lower valleys and plateaus of this region are comparable, as pointed out by Woeikof, with the Aral-Caspian lowland. The most extreme deserts of the Old World are, however, more absolutely barren than the North American deserts.

It is convenient to consider the Plateau Province in two divisions, the northern and the southern. The most striking feature on the precipitation map is the increased rainfall over the dominant mountain groups of Idaho (Bitter Root, Clearwater, and Salmon River mountains) and of eastern Oregon (Blue Mountains). Annual amounts of 30 and 35 in. are shown over the upper slopes, with the isohyetal line of 40 in. inclosing a portion of the northern Bitter Root Range. These are the largest amounts (40 in.) shown anywhere in the Rocky Mountain area. Over the districts of least elevation, namely, the

Snake River plains in southwestern Idaho and the great plains of southeastern and central Oregon and central Washington, rainfalls of less than 10 in. occur. Lying between the somewhat more abundant rainfall on the mountains and the too great aridity of the districts with less than 10 in., a fair portion of eastern Oregon and Washington and of southern Idaho has from 10 to 20 in. In certain of these districts dry farming has been carried on with a considerable degree of success, especially in the newly developed and fertile agricultural region of eastern Washington. Briggs and Belz have concluded that with the evaporation which occurs in the Great Basin a mean annual rainfall of 13 in. is about the minimum for profitable dry farming. In the basin of the Columbia River, in southern Washington and northern Oregon, wheat is successfully grown by summer-fallowing methods with a mean annual rainfall of 10 in., and the minimum for any profit at all seems to be about 8.50 in. As these authors point out, there is probably no other part of these states where dry farming is practiced with so small a rainfall as this.

Land with too little rainfall even for dry farming, and not possible of irrigation, is to a considerable extent used for grazing, and irrigation has brought great prosperity to a number of communities which have become famous for their fruit crops; for example, the Yakima valley in Washington. A railroad trip of great interest may be taken from the famous dry-farming wheat country around Spokane, southward on the treeless lava plateau, across the Columbia River, and then westward and northwestward up the valley of the Yakima River in the lee of the Cascade Mountains. Here man has turned the desert into one continuous garden. Here the wonderful orchards of apple, peach, and pear trees, the fields of hops and of alfalfa, and the vineyards reaching for miles and miles in every direction make the traveler realize that the glowing accounts which have been given of this region are not greatly exaggerated. Upon the summits and upper slopes of the Cascades there is a rainfall ten or fifteen times as great as that in the valleys at the eastern base—a rainfall resulting from the presence of the mountains across the path of the rain-bringing westerly winds.

It is this water which has been collected for the use of man in the Yakima irrigation projects. The interest of the climatologist in this Yakima country is not so much in the number of carloads of fruit which are sent out or in the size of the apples, and pears, or peaches, but rather in the relation of the dry, leeward, rain-shadow valleys to the well-watered mountain summits, and in the curious overlapping of the forests from the rainy western slopes into the higher portions of the valleys on the eastern slopes.

The Rocky Mountains as a whole, it should be noted, are not nearly as important controls of precipitation as might at first be expected. They are, in general, so far from the Pacific that their rainfall is not heavy. They are, furthermore, to leeward of the very considerable ranges of the Sierra Nevada and the Cascades. The rain-shadow effect of the Cascades is strikingly shown on the rainfall map in the contrast between the rainy western slopes and the dry eastern slopes in Washington and Oregon.

The southern division of the Plateau Province is distinctly drier than the northern. With the exception of some local areas in the mountains the rainfall is less than 20 in., mostly below 10 in.; over no insignificant portion it is even below 5 in. Well removed from the most frequented track of cyclonic storms; in the lee of the great Sierra Nevada; shut off from the free access of rain-bearing winds, it is no wonder that this great province should be arid. Not many years ago this was all known as the "Great American Desert." It is a region of interior drainage, of peculiar topographic forms dependent on the climate, and of Great Salt Lake, the feeble relic of a great ancestor, Lake Bonneville. The real "American Desert" lies in southeastern California, the southwestern angle of Arizona, and western Nevada. If the continent were broader, there would be a much larger desert in these latitudes. The mean annual rainfall is only 5 in. Death Valley is here, with its famous borax deposits and its intense summer heat. The Salton Sea is here,—an anomaly in a true desert,—originally supplied through the Colorado River by water which fell as rain or snow on the slopes of the Rocky Mountains far to the east;

evaporating rapidly under the clear skies and high temperatures. The Black Rock desert and the "sinks" and soda deposits of western Nevada are here.

Surrounding the "desert," with its hopelessly deficient rainfall, comes a considerably larger area with from 5 to 10 in., also arid and impossible for agriculture and for settlement without irrigation. This includes most of Nevada, western Utah, a strip across western Arizona, and other areas of relatively moderate elevation in northern Arizona, New Mexico, eastern Utah, and southwestern Wyoming. Over the higher mountain slopes and plateaus the amounts exceed 20 in. locally; for example, across the central portion of the Arizona plateau or on the Wasatch and Uinta mountains of Utah, the Absaroka, Wind River, and other ranges of northwestern Wyoming (over 25 in. on the Absaroka Range), and the San Juan (over 30 in.) and other mountains of western Colorado. Intermediate rainfalls from 10 through 15 to 20 in. are found distributed, in close agreement with the topography, over the intermediate altitudes. A topographic map is here a good rainfall map and also a good vegetation map. For while the lower-lying portions of this whole region are dry and barren, the increased precipitation over the more elevated plateaus and on the mountains supports grass and often forests. Arizona, which rises more or less like a flight of steps from the southwestern corner, shows this relation very clearly. From a mean rainfall of less than 5 in. in its southwest, the amounts gradually increase to over 20 in. The so-called "islands"—much more appropriately termed *lakes*—of heavier precipitation on the mountains are economically of great importance. They supply the water, chiefly melted snow, which is used for irrigating the arid lowlands. Phoenix, Arizona, for example, receives on the average less than 8 in. of rainfall annually. Over the watershed behind the Roosevelt Dam perhaps twice as much rain falls. This extra supply, resulting from the presence of the mountains, when carefully collected, stored, and distributed, makes the glory of the Salt River valley, of which Arizona is so justly proud.

Wherever throughout this province the streams, supplied by the melting snows of the higher mountains, afford sufficient

water for irrigation, bountiful crops await the farmer. But the water supply is limited, and many of the far too optimistic hopes for the future of the region have already been disappointed. Only where there is mineral wealth in the form of precious metals or of salts is there any value in land which has insufficient rainfall for farming and which cannot be irrigated.

Rainfall of the Pacific Coast. Rainfall and topography are also very closely related on the Pacific slope. The heaviest rainfalls in the United States (over 120 in.) occur on the Olympic Mountains of northwestern Washington. These are also among the heavy rainfalls of the world. More than 100 in. are indicated on the map for two small localities on the northern Coast Range of Washington and Oregon. Elsewhere the largest amounts are 80 in. These are shown over the higher slopes and summits of the Cascade Range, over a small portion of the northern Sierra Nevada, and on the Coast Range as far south as northern California.

To the south the rainfalls on the mountains decrease rapidly, although, as compared with the lowlands, they remain relatively very heavy. The 50-inch line on the Sierra Nevada does not extend south beyond the latitude of San Francisco; the 30-inch line reaches a little beyond the latitude of Fresno. The mountains of southern California are clearly shown on the map by their rainfalls of over 25 in. Many streams, deep and swiftly flowing, rush down the slopes of these Pacific coast mountains, supplying vast and never-failing water power. The name of the Cascades at once suggests heavy precipitation. Here, in the future, when lumbering has ceased to be the chief industry, the varied manufacturing and industrial enterprises of a more complex and more thickly settled community will be developed by means of this water power, one of the most important assets of the Pacific slope.

Beautiful climatic cross sections, contrasting the rainy windward and dry leeward sides, may be obtained when crossing either the Cascades or the Sierra Nevada by train. The contrast between the treeless lower lands east of the Cascades in Washington and the densely forested western slopes is wonderfully impressive. In traveling by train from The Dalles of the

Columbia River down the river to Portland, Oregon, the change in the character of the vegetation is an excellent "car-window" observation of the increase of rainfall, which just about trebles between The Dalles and Portland (from 15 to 45 in.). The gorge of the Columbia River, it may be noted, is distinctly indicated by the isohyetal lines on the rainfall map. Again, in crossing the Sierra Nevada Mountains on the railroad, going east from San Francisco, the traveler cannot fail to notice that the green slopes and forests of the Pacific side are rapidly replaced by the sagebrush and allied forms of vegetation on the east. From a precipitation of about 50 in. the descent takes place with remarkable suddenness into the Nevada desert, with its alkali flats, its dust, and its less than 10 in. of rainfall. Railroads crossing these mountains are not infrequently subjected to heavy expenses on account of washouts resulting from the heavy rainfalls. Occasionally local landslides, caused by excessive downpours, add to the difficulties.

The heavy rainfalls of the northern Pacific coast are similar in origin to those of the coasts of Scotland and of Norway and of Chile. The close proximity of the Pacific Ocean, from which the prevailing winds blow; the frequency, especially in winter, of cyclonic storms whose inflowing winds from several quarters are well charged with moisture; the mountain barriers in the path of the onshore winds,—these are the dominant controls. In winter the land (especially the high land) is usually much colder than the ocean, and hence the onshore winds, blowing from the warm Pacific, readily become damp and rainy. This condition combines with the greater storminess of the winter months to produce the Pacific type of rainfall, with its well-marked winter maximum. Even if there were no high mountains over the northern Pacific coast, the rainfall would doubtless still be ample for agricultural needs. The storm control is not dependent on topography. The southern portion of the Pacific coast is drier for several reasons. It is beyond the reach of most of the rain-bringing storms which pass across the northern sections. The lands, and even the mountain slopes, are warmer for much of the year, especially in summer, than the cool ocean, and the onshore winds become warmer and therefore drier. The

prevailing winds also have a considerable northerly component, and are for that reason warming and hence drying winds.

In low latitudes within the easterly trade wind belts, mountains on the western border of a continent (the Cordillera of South America, for example) obviously have no rain-shadow effect on the interior. In the belt of prevailing westerly winds, per contra, a western mountain barrier, especially a double western mountain barrier, must necessarily become a marked rainfall divide, as in the United States. In Europe, with its more open western borders, there is no very marked rain-shadow effect. Scandinavia alone, with its drier interior (eastern) districts, presents a weak analogy with the United States.

The smallest rainfalls on the Pacific slope (excluding southeastern California) are those of the San Joaquin valley (under 10 in.). This is clearly a topographic, rain-shadow effect. Going northward up the valley of California, the rainfall gradually increases. Over most of the lower portions of the Sacramento valley it is between 15 and 20 in. The surrounding slopes all show heavier rainfalls, and the amounts increase rapidly at the northern end of the Sacramento valley as the altitudes increase. San Diego, on the extreme southern coast, has about 10 in. The increase with latitude up to 100 in. on the coast of Washington is just the opposite condition to that which is found on the Atlantic coast, where there is a decrease from Florida to Maine. The Willamette valley of Oregon has less rainfall than the mountain ranges on both sides, but is abundantly watered (from 40 to 50 in.). In the extreme north and the extreme south of the intermontane lowlands of western Washington and Oregon there are small areas, distinctly topographically controlled, of less than 30 in. In the Rogue River valley in southern Oregon some of the fruit-growers irrigate with a rainfall of about 30 in.

Irrigation is absolutely essential over large sections of southern California. Of vast importance in the economic value of the southern counties of California is the very heavy winter snowfall on the Sierras. This supplies many streams that flow out over the lowlands, and is the source of abundant water for power, for irrigation, and for city and household use. The

Sierra Nevada Mountains ("snowy ranges") well deserve their name. To them California owes much if not most of her present prosperity and of her promise for future growth and development. The many feet of winter snowfall which accumulate on these upper slopes mean millions upon millions of dollars each year to the farmers and fruit-growers of southern California. Were all this precipitation to fall as rain, every winter would witness devastating floods, and every summer would wither and destroy the crops. The amount of rain and snowfall, it should be noted, does not increase at a uniform rate all the way up the western slopes to the summits of the highest mountains. In his careful hydrographic work in connection with the Los Angeles aqueduct, C. H. Lee found that "precipitation on the west slope of the Sierra between the Yuba and Tuolumne rivers increases at a variable rate, which, expressed as an average, is 0.85 in. per 100-foot rise from the floor of the Great Valley to the 5000-foot contour. Above the 5000-foot contour it decreases approximately at the rate of 0.40 in. per 100-foot rise to the crest of the Sierra."[1]

Rainy Winds. The directions of the chief rain-bearing winds vary somewhat in different sections of the country. They

[1] C. H. Lee, "Precipitation and Altitude in the Sierra," *M. W. R.*, Vol. 39 (1911), pp. 1092–1099. For cross sections of topography and rainfall see also Homer Hamlin, "Water Resources of the Salinas Valley, California," *U. S. Geol. Surv. Water-Supply and Irrigation Paper No. 89* (1904), Fig. 1 on page 41 and Fig. 2 on page 42; E. L. Wells, "Precipitation in Oregon," *M. W. R.*, Vol. 50 (1922), pp. 405–411. There are many discussions of rainfall of the United States as a whole, as well as of individual sections and states. The following list, arranged alphabetically, contains the more important general recent publications dealing with the mean annual precipitation which have not already been referred to. The titles do not include discussions or maps of the rainfall of special districts.

F. H. Bigelow, "The Daily Normal Temperature and the Daily Normal Precipitation of the United States," *U. S. Weather Bur. Bull. R*, 1908.

Henry Gannett, Rainfall Maps of the United States. These have been published as follows: in *14th Ann. Rept. U. S. Geol. Surv. for 1902–1903*, Part II (1894), Plate VI; *M. W. R.*, Vol. 30 (1902), Plate 40; *U. S. Geol. Surv. Water-Supply Paper No. 234* (1909), Plate I; ibid., No. 301 (1912), Plate I; also as Plate I in each number from 302 to 312 (1912–1914).

M. W. Harrington, "Rainfall and Snow of the United States, Compiled to the End of 1891, with Annual, Seasonal, Monthly, and Other Charts," *U. S. Weather Bur. Bull. C*, 1894, Atlas and Text (short bibliography, pp. 8–9).

A. J. Henry, "Average Annual Precipitation in the United States for the Period 1871–1901," *M. W. R.*, Vol. 30 (1902), pp. 207–213, Chart XII; "Climatology of the United States," *U. S. Weather Bur. Bull. Q*, 1906 (pp. 47–59 on precipitation).

depend upon the location of the source of the water vapor, the nature of the intervening country, the cyclonic tracks, local topography, and other controls. They also vary more or less with the season.[1] From a general climatic point of view, details regarding rain-bearing winds are not needed. Summarizing broadly, and without regard to seasonal variations, southeasterly to southerly winds are rainy over the Eastern Province, with modifications (northeast-south) over much of the Atlantic coast, especially in the north and in the Gulf Province (northeast-southeast). In the Plains southeasterly to southerly and, in the north, southwesterly winds are as a whole the rainy ones. Over the Plateau local topography is a significant control; but, speaking generally, the southeasterly to southwesterly winds are the rain-bearers, and the same is true of the Pacific Province. The general tendency all over the United States toward rain with southerly winds is obvious. These are prevailingly associated with cyclonic disturbances passing by to the northward. Along the Atlantic coast, and also to a less extent in the lake region and north of the Gulf of Mexico, northeasterly winds are also rain-bearing.

Mark Jefferson, "Aridity and Humidity Maps of the United States," *Geogr. Rev.*, Vol. 1 (1916), pp. 203–208.

W. G. Reed, "Cyclonic Distribution of Rainfall in the United States," *M. W. R.*, Vol. 39 (1911), pp. 1609–1615.

Atlas of Meteorology, Plate 21; text page 20.

"Bibliography of Meteorology. A Classed Catalogue of the Printed Literature of Meteorology from the Origin of Printing to the Close of 1881; with a Supplement to the Close of 1889, and an Author Index." Prepared under the Direction of Brigadier General A. W. Greely, Chief Signal Officer, U. S. A. Edited by Oliver L. Fassig. Washington, 1891; Part II: Moisture, pp. 237–242.

Summaries of Climatological Data of the United States by Sections, *U. S. Weather Bur. Bull. W*, 1914 and later years (contains monthly and annual mean rainfalls, year by year, since the beginning of the observations).

See also the list of selected references in J. B. Kincer, Precipitation and Humidity section of *Atlas of American Agriculture*, Part II: Climate (1922), p. 4.

[1] This subject has received some attention because of its importance in weather forecasting. See, for example, "Rain and Dry Winds Computed for Different Geographical Districts," *Annual Report of the Chief Signal Officer for 1878* (1879), pp. 616–634 (gives directions of rain-bearing winds at Signal Service stations; no maps); E. B. Garriott, "Weather Folk-Lore and Local Weather Signs," *Weather Bur. Bull. No. 33* (1903), pp. 49–153 (summaries of local weather signs at Weather Bureau stations and seasonal charts showing the wind directions which usually precede rain or snow); F. Waldo, "Elementary Meteorology" (1896), p. 361 (Fig. 120, p. 362, shows wind directions most likely to be followed by rain).

CHAPTER IX

RAINFALL TYPES AND MONTHLY AND SEASONAL RAINFALL

IMPORTANCE OF RAINFALL TYPES · RAINFALL TYPES AND THE METHOD OF ILLUSTRATING THEM · RAINFALL TYPES OF THE EASTERN PROVINCE · RAINFALL TYPES OF THE GULF PROVINCE · RAINFALL TYPES OF THE PLAINS PROVINCE · RAINFALL TYPES OF THE PLATEAU PROVINCE · RAINFALL TYPES OF THE PACIFIC PROVINCE · RAINY SEASONS · MONTHLY AND SEASONAL RAINFALL MAPS: GENERAL · THE LARGER FACTS BROUGHT OUT ON THE CHARTS · SEASONAL RAINFALL ON THE PACIFIC COAST · SEASONAL RAINFALL IN THE PLATEAU PROVINCE · SEASONAL RAINFALL OVER THE PLAINS · SEASONAL RAINFALL IN THE EASTERN AND GULF PROVINCES · GENERAL SEASONAL DISTRIBUTION OF PRECIPITATION

Importance of Rainfall Types. "When does the rain come?" is a question the correct answer to which often concerns the farmer and the engineer more than does the answer to the question "How much rain falls in a year?" A relatively small amount of precipitation may be so distributed that most of it comes just when the crops have the greatest need of it. In the United States great progress has been made in agriculture, especially in the semi-arid regions, through the selection of crops whose periods of growth and of maturity coincide with the season of most abundant rainfall. In earlier years failure often resulted from an attempt to raise crops which were not adapted to the rainfall type of their particular district. Soil conditions depend to no small degree on the season at which most of the rain falls.[1] There must inevitably be a consider-

[1] The most fertile soils are in the region where more rain falls in early summer than in late summer, and vice versa. Poor, sandy soils are characteristic of regions of late summer rains (R. M. Harper, "A New Seasonal Precipitation Factor of Interest to Geographers and Agriculturists," *Science* (N. S.), Vol. 48 (1918), pp. 208–211). See also idem, "Some Interesting Relations between Vegetation and Mineral Deposits," *Engin. and Min. Journ.*, Vol. 112 (1921), pp. 693–694.

able difference in the processes of weathering between two places one of which has dry summers and the other of which has rainy summers. The rainfall type is thus both directly and indirectly important in agriculture: directly, as furnishing the rainfall for the immediate use of the plants, and indirectly, through the relation of the rainfall season to the processes of weathering and of soil formation. The water available for mills, for electric-power plants, for irrigation, for water supply, also depends upon the rainfall type. The latter determines the size of the reservoirs, the length of the period needed for the storage of the water, the loss by evaporation—in short, the general availability of the water supply. The desirability of a region as a health or as a pleasure resort depends largely upon the season at which the most or the least rain falls.

Rainfall Types and the Method of Illustrating them. The rainfall types here adopted are based upon an examination of a large number of plotted monthly rainfall amounts for selected stations in all parts of the United States, and upon a comparison of the curves thus obtained with the rainfall types suggested by Greely,[1] Henry,[2] and Kincer.[3]

[1] A. W. Greely, "Rainfall Types of the United States," *Nat. Geogr. Mag.*, Vol. 5 (1893), pp. 45–58, Plate 20.

[2] A. J. Henry, "Rainfall of the United States, with Annual, Seasonal, and Other Charts," *U. S. Weather Bur. Bull. D,* 1897 (pp. 11–13 and Plate 1 concern rainfall types); idem, "Climatology of the United States," *U. S. Weather Bur. Bull. Q,* 1906 (pp. 50–51 and Plate 27 concern rainfall types).

[3] J. B. Kincer, Precipitation and Humidity section of *Atlas of American Agriculture,* Part II: Climate (1922), pp. 16, 37, Fig. 13 (six principal rainfall types are given, designated as Pacific, Sub-Pacific, Arizona, Plains, Eastern, and Florida. These types are illustrated in Fig. 13. The three most significant, "considering the areas covered and their climatic importance," are the Pacific, the Plains, and the Eastern).

In addition to the foregoing publications on rainfall types, the following may be found useful: Cleveland Abbe, "Seasonal Rainfall Régimes in the United States," *M. W. R.*, Vol. 32 (1904), pp. 470–471; F. L. Wachenheim, "Die Hydrometeore des gemässigten Nordamerika," *Met. Zeitschr.*, Vol. 22 (1905), pp. 193–211; W. B. Stockman, "Periodic Variation of Rainfall in the Arid Region," *U. S. Weather Bur. Bull. N*, 1905; W. G. Reed, "Climatic Provinces of the Western United States," *Bull. Amer. Geogr. Soc.*, Vol. 47 (1915), pp. 1–19; Cleve Hallenbeck, "Precipitation over the Southeast Rocky Mountain Slope," *M. W. R.*, Vol. 44 (1916), pp. 341–342; E. L. Wells, "Precipitation in Oregon," ibid., Vol. 50 (1922), pp. 405–411; J. B. Kincer, "The Climate of the Great Plains as a Factor in their Utilization," in *Annals Assoc. Amer. Geogr.*, Vol. 13, No. 2 (1923), pp. 67–80, especially p. 70; *Summaries of Climatological Data by Sections,* for 1914 and later dates. The earlier work of Blodget and especially of Schott contains much that is still of interest.

Each type or sub-type of the present classification is illustrated by a curve showing the monthly amounts of rainfall. These curves are composites. Each one is based upon the records from several (usually five or six) stations in the same general district. There is a distinct advantage in using a composite curve instead of the curve for a single station. When the data for several stations are combined, individual local peculiarities and errors arising from the topography, the altitude, the exposure of the gauge, and from other local controls, are to a considerable degree neutralized. For the purposes of a general comparative study the composite curve is thus more useful than the curve for a single station. Two things should be borne in mind when considering rainfall types. First, it must not be expected that the curve for any individual station will agree absolutely with the type curve for the district. These composite curves show the dominant type of rainfall distribution over the areas for which they have been selected as illustrations. Many individual stations over these same districts naturally depart more or less from the type, especially toward the margins of the areas. Second, the distribution of rainfall at a station in any given year often differs considerably from the general type, which is based upon the records of many years.

Each of the accompanying curves is plotted on the same scale. The height of the diagram therefore gives at a glance an indication of the amounts of rainfall. The approximate annual rainfalls over the district for which the curves are representative are noted in each case. Although the type and not the amount is here under discussion, some general idea of the monthly amounts of precipitation is inevitably gained by even a hasty glance at the curves. This knowledge is useful in the further study of rainfall. The general location of each type is indicated on the accompanying map (Fig. 56). The solid black lines indicate the climatic provinces of the United States. Except in the few cases where well-defined mountain barriers intervene, as in the case of part of the Sierra Nevada-Cascade and Rocky Mountain divides, one rainfall type naturally merges gradually into the neighboring one. There are,

therefore, few sharp division lines. The boundaries shown on the map are not to be taken as indicating sudden transitions.

Rainfall Types of the Eastern Province. The outstanding fact regarding the seasonal rainfall over most of the great area which lies east of the Rocky Mountains is the predominance of summer rains. Such a distribution is entirely in accord with the general continental character of the climate of this area as a

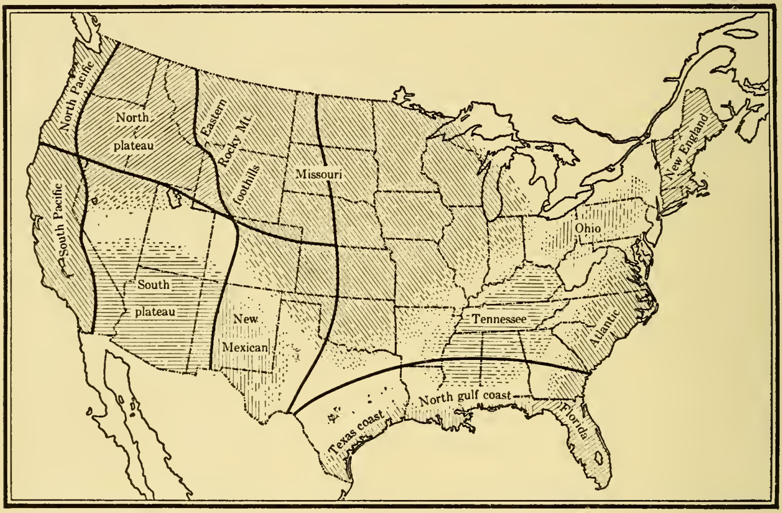

FIG. 56. Geographical Distribution of Rainfall Types

whole. Warm-season rains are typically the rains of continental interiors. They occur when the continental indraft of the warmer months brings in warm, damp air from the surrounding water areas and when high temperatures favor local showers.

The most characteristic rainfall type of the Eastern Province, both because it covers the largest area and because its curve so emphatically indicates continental control, is that which, following Greely, is named *Missouri*. This type prevails over most of the Plains Province, extends eastward well over the prairie states and into the Great Lakes region, and is found as far south as northern Texas. Fig. 57 is a composite curve illustrating the Missouri type. The winter precipitation is light.

Most of the year's supply of rainfall comes in late spring and early summer. The maximum is in June at many stations, but May and June, or May, June, and July, may have about equal amounts. Over most of the Great Plains 70–80 per cent of the annual precipitation falls in the six warmer months. Similar conditions are found over the Russian steppes, as pointed out by Woeikof. This type of rainfall brings the maximum at the season when rainfall is most needed by the crops. While such a distribution may be of relatively little importance in a region where the total annual precipitation is more than enough for agricultural uses, it is obviously of great moment where the year's rainfall at best scarcely suffices for the demands of the staple crops.

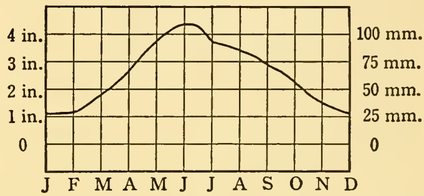

FIG. 57. Missouri Type
Mean annual rainfall, 20–30 inches

While the area embraced by the Missouri type is very extended, the general character of the curve is maintained with extraordinary persistence. Toward the margins of the district, to the east, south, and west, certain modifications are noted. A number of stations around the upper Lakes—for example, in eastern Minnesota, eastern Wisconsin, the upper peninsula of Michigan, etc.—have the Missouri primary maximum in June and a secondary maximum in September. In going east, also, as the vicinity of the lower Lakes and of the Ohio valley is reached, the precipitation of the winter months becomes distinctly more marked. It is advisable, therefore, to set apart the *Ohio* type, whose general location is indicated on the map (Fig. 56) and whose curve is illustrated in Fig. 58. The continental summer maximum of the Missouri type, here somewhat retarded into July, is still clearly shown, but the increase in winter rainfall and the resulting smaller annual range are marked. The location of this Ohio area in a part of the country where cyclonic rainfalls are both frequent and abundant, and where the winter and spring cyclones from the southwest and from the Gulf of Mexico are particularly heavy rain-bringers,

sufficiently explains the wet winters of the Ohio type. The Ohio type is essentially the Missouri type with somewhat more cyclonic rain added during the winter. The winter precipitation of the Ohio type is heavier than that in the Great Lakes region generally and is more often rain, whereas over the Great Lakes themselves, especially the upper Lakes, more snow falls.

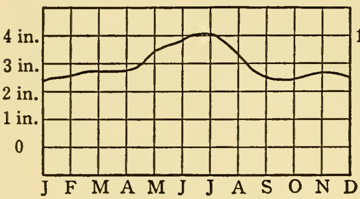

FIG. 58. Ohio Type
Mean annual rainfall, 35–40 inches

Still farther east the distribution of rainfall through the year becomes more and more uniform, especially as that interesting northeastern section of the country is reached which, sooner or later, comes within the rain area of most of the storms which pass over the United States. In the type which may be called *New England* we have the most uniform distribution of precipitation which prevails anywhere in the whole country (Fig. 59). The variation from month to month is too slight to be of any economic importance. Droughts are about as likely to occur in one season as in another, but are, of course, more critical in summer. Throughout the year there is usually enough water to keep the rivers well supplied and available for power. Maxima and minima can hardly be said to occur, although August, in the long run, is somewhat the rainiest month. This, as will be seen in a moment, is a marked characteristic of the seaboard district along the southern Atlantic coast. The New England curve is obviously affected by controls which dominate the rainfall types of adjacent regions. Some of the stations show a tendency to a slight November maximum, which is a characteristic of the St. Lawrence valley

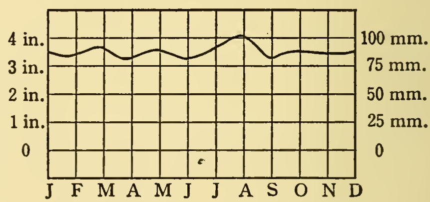

FIG. 59. New England Type
Mean annual rainfall, 40–45 inches

(Greely). This uniform distribution of rainfall is seen, more or less clearly, over the area directly west and southwest of New England. New York City, Philadelphia, Washington, all have rainfall curves which do not differ greatly from the composite shown in Fig. 59 or from the curve of Boston. With increasing distance from the coast the tendency toward a midsummer (July) maximum becomes more marked.

Farther south, over the Atlantic coast states lying between Virginia and Florida, there is a well-defined late-summer maximum, usually in August; a minimum in middle or late autumn (October or November); a secondary maximum in late winter (March); and a secondary minimum in spring (April). Hann selected the Atlantic coast of North America in latitude 40° N. as being a typical example of extra-tropical coast rains with a dry spring. The percentages of rainfall by seasons are as follows:

December–February	March–May	June–August	September–November
24	23	27	26

This type, which is best termed the *Atlantic*, gradually merges on the north into the very uniform rainfall distribution just considered, which attains its most characteristic development in New England. On the south the Atlantic type merges into that of Florida. Fig. 60, based on records from stations in North and South Carolina and Georgia, illustrates the Atlantic type. The late-summer maximum, which is best marked on the coast, is controlled by the frequent and heavy thundershowers of the warmest months, together with the additional precipitation which comes in connection with occasional West Indian hurricanes. The winter rains result from the general cyclonic storms of that season. The Atlantic type,

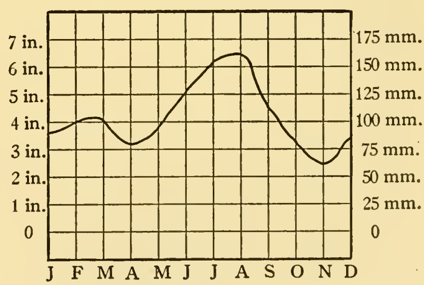

FIG. 60. Atlantic Type
Mean annual rainfall, 45–50 inches

with its abundant supply of rainfall throughout the year, is obviously well adapted to furnish water power at all seasons, and its warm-season maximum is favorable for crops.

Over the whole great region east of the Rocky Mountain divide there is but one rainfall type which has a single maximum in winter. This prevails over Tennessee and parts of the adjoining states, especially those immediately to the north and south, and was therefore named the *Tennessee* type by Greely. Because of its prevalence over the southern portions of the Appalachian Mountains, Henry has called it Southern Appalachian and Tennessee. The curve given in Fig. 61 illustrates this type. There is a single maximum in late winter or early spring (March) and a well-marked minimum in mid-autumn (October), when the general storm control is relatively inactive. Droughts are not infrequent in the autumn, with occasional damage to crops. Toward the margins of the Tennessee area, both on the east and on the south, the tendency to a second maximum in middle or late summer is very noticeable. The warm and damp southerly winds of the cyclonic storms of late winter and spring which cross this area on their way north from Texas or the Gulf are responsible for the heavy rainfall of the Tennessee maximum, just as they bring the winter rains of the Ohio type, previously noted. These late winter and early spring rains not infrequently cause floods in the rivers of this region. Topography is an important factor in causing locally excessive precipitation.

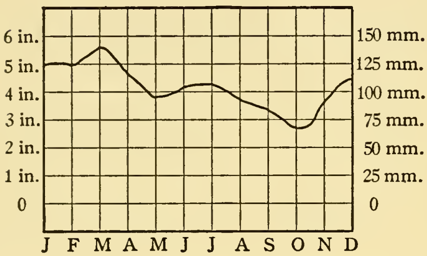

FIG. 61. Tennessee Type
Mean annual rainfall, 45–55 inches

Rainfall Types of the Gulf Province. The Gulf Province is overlapped on the north and northeast by the Tennessee and Atlantic types. Its own rainfall distribution is complex and cannot be generalized into a single type. As a whole, the rainiest season is late summer or early autumn. These condi-

tions are satisfactorily explained by the fact that the warm and moist prevailing summer winds over this area come directly from the Atlantic Ocean and from the Gulf of Mexico, that thunderstorms are of frequent occurrence, and that local cyclonic depressions and West Indian hurricanes contribute their share of precipitation. Although the Gulf Province is a small one, three rainfall types may be distinguished. A type which may be called the *Florida* is distinctly tropical in character (Fig. 62). From June to September or October there is a true rainy season, the maximum on the east coast tending to come later (September–October) than on the west coast (July–August). These are local convectional thunderstorm rainfalls. Florida is also much exposed to tropical hurricanes, which not infrequently bring their characteristic destructive gales and flooding downpours and are the chief cause of the autumn maximum of rainfall on the east coast. A faint secondary maximum is noted in winter. Because of the dry autumn and spring in northern Florida much interest has there been taken in sub-surface and surface irrigation. Along the northern Gulf coast there is a complex type which may be called the *North Gulf Coast* type, with a late winter and early spring secondary maximum similar to the primary maximum of the Tennessee type, and a primary midsummer

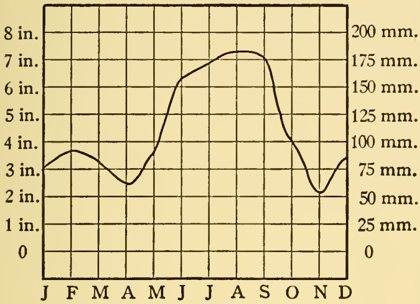

FIG. 62. Florida Type
Mean annual rainfall, 50–55 inches

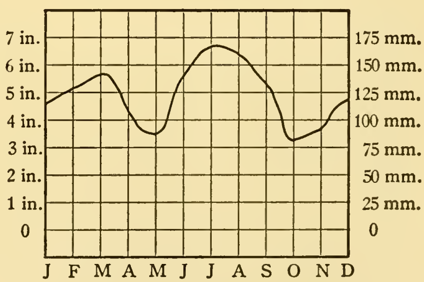

FIG. 63. North Gulf Coast Type
Mean annual rainfall, 55–60+ inches

or late-summer maximum (July–August) which suggests the Atlantic type (Fig. 63).

The tendency toward the August–September maximum of Florida becomes more and more marked on going eastward along the northern Gulf coast. On the Texas coast there is a marked early-fall (September) maximum, as illustrated in Fig. 64. This is designated the *Texas Coast* type. The curve is so different from the two other curves of the Gulf Province that it deserves a special name, although it occupies but a limited area on the coast of Texas. Farther inland the Texas stations show more and more tendency toward an earlier maximum like that of the Missouri type, and there is an intermediate belt of country in which a transition type is found, with the September maximum of the coast and the early-summer maximum of the interior.[1]

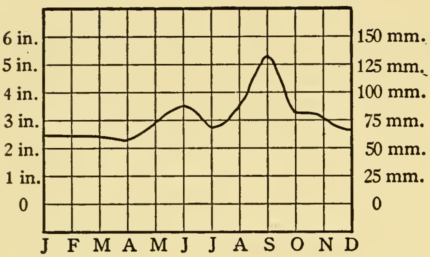

FIG. 64. Texas Coast Type
Mean annual rainfall, 25–45+ inches

Rainfall Types of the Plains Province. The dominant rainfall type over the northern Plains is that already described as the Missouri (Fig. 57). The economic importance of this type of rainfall is much greater over the Plains, where the annual rainfall is either insufficient or barely sufficient for agriculture, than it is farther east, where the annual precipitation is heavier and the season at which the rain comes makes less difference. It may without exaggeration be said that if a man were allowed 20 in. or less of precipitation a year, and were told to

[1] A. W. Greely, "Some Peculiarities in the Rainfall of Texas," *Bull. Phil. Soc. Washington*, Vol. 12 (1892), pp. 53–65. In a discussion of the rainfall of the southern Texas coast Tannehill has pointed out that the reason why Corpus Christi has less summer rain than Galveston is because the strong southeast wind from the Gulf, which is essentially monsoonal in character, interferes with the building up of summer cumuli and cumulo-nimbi. In other words, convectional processes go on along the northern coast of the Gulf but are interrupted on the southern coast (I. R. Tannehill, "Wind Velocity and Rain Frequency on the South Texas Coast," *M. W. R.*, Vol. 49 (1921), pp. 498–499). See also I. R. Tannehill, "Some Characteristics of Texas Rainfall," ibid., Vol. 51 (1923), pp. 250–253.

distribute this amount throughout the year so that it might be of the greatest benefit to the crops over an area like that of the northern and central Great Plains, he could not devise any type of distribution more favorable than that of the Missouri type. The moisture which supplies these beneficent rains comes chiefly from the Gulf of Mexico, but probably also to some extent from the waters of the Great Lakes. The spring and early-summer maximum is essentially due to thundershowers—both those which are simply local convectional overturnings of heated air (heat thunderstorms) and those which occur in connection with the relatively weak cyclonic depressions of the hotter months. These summer rains are important in supplementing the water supply which is obtained by the use of the rivers. As pointed out by Greely: "It is well known that the annual rainfall is small, yet eastern Nebraska receives, during these four months, April to July inclusive, a larger amount of rainfall than the interior portions of the eastern states from Maine to Virginia; and western Nebraska receives only a slightly lesser amount." [1] These rains of spring and early summer are either of direct benefit in falling upon the growing crops, or of indirect benefit in coming at a time when they are of most use for irrigation. It is readily seen that there is a distinct advantage in having the rainfall maximum over before the harvesting season. The relatively dry autumns are favorable to the occurrence and spreading of prairie fires, about which much used to be heard. The very moderate winter precipitation, which is mostly snow except in the southern sections, has the advantage of being generally so light and dry that the cattle ranges are not rendered inaccessible. It is, furthermore, an excellent protection for the forage grasses and keeps the soil from freezing deeply. In the foothills the winter winds blow this light snow into the gullies and hollows, leaving much of the open country bare for grazing.

The Missouri type extends well into the climatic province of the Southern Plains, but, as is to be expected, the simple type illustrated in Fig. 57 gradually loses its distinguishing

[1] A. W. Greely, "Rainfall Types of the United States," *Nat. Geogr. Mag.*, Vol. 5 (1893), pp. 45–58.

character and becomes more complex. Thus, in eastern Colorado, in western Texas, and in Oklahoma there are many transitional types which show the earmarks of adjacent rainfall types of different character, and often have two maxima. Along the eastern base of the Rocky Mountains, chiefly in the Northern Plains Province but also extending across into the Southern Plains Province, the maximum comes in May (or even April) rather than in June. This may be considered a slight modification of the pure Missouri type and may be called the *Eastern Rocky Mountain Foothills* type (Henry). The curve is shown in Fig. 65, and its general location is indicated on the map (Fig. 56). There is comparatively little winter precipitation because of the cold, and the maximum thunderstorm activity is over by June.

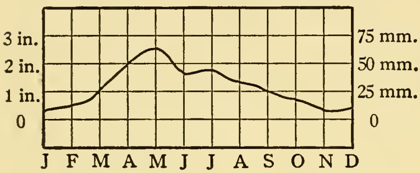

FIG. 65. Eastern Rocky Mountain Foothills Type

Mean annual rainfall, 10–15 inches

In the southwestern corner of the Plains Province, in New Mexico and in extreme western ("Trans-Pecos") Texas, there is a simple rainfall type (illustrated in Fig. 66) with a dry winter and a well-marked midsummer or late-summer rainfall maximum (July–August). This somewhat resembles the Missouri type, but has drier winters and a later maximum. The winters of this type, which is called the *New Mexican*, are dry because the district is well removed from sources of moisture and because it is visited by but few cyclones, of which not many bring precipitation of consequence. The summer rains come in local thunderstorms, which occur with great regularity, frequency, and intensity over the heated mountains and plateaus of this semi-arid area. Most of this summer precipitation is available for crops only indirectly, through irrigation. The rainfall of this type comes mostly in showers of comparatively short duration. Outdoor occupations are thus seldom long interrupted by wet weather.

Rainfall Types of the Plateau Province. The rainfall types of the great intermountain Plateau Province are interesting be-

cause of their transitional character. As a whole, the dominant characteristic of the rainfall distribution west of the Rocky Mountains is the cold-season maximum (except over the southern portion of the Southern Plateau Province). This is especially marked on the Pacific slope. The summer maxima east of the Rockies and the winter or spring maxima west of them are found more or less commingled in the Plateau Province. Thus we here find a combination of the marine rainfall régime of the Pacific coast and the continental régime of the interior.

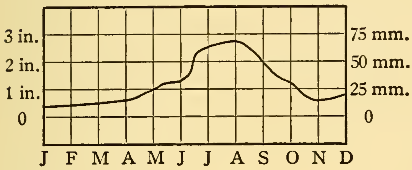

FIG. 66. New Mexican Type
Mean annual rainfall, 10–15 inches

Two well-defined rainfall types may be distinguished, one in the north, the other in the south. The rainfall distribution over the Northern Plateau Province, which may be called the *North Plateau* type, is illustrated in Fig. 67. On the whole, except for a dry summer, the distribution of precipitation is fairly uniform through the year. There is a winter maximum, marine in character, and a midsummer or late-summer minimum (July–August), but there is often an increase in the rainfall toward the end of winter, reaching a secondary maximum in late spring. This is a continental feature, not found on the narrow Pacific coast. Some stations in this district have one maximum only, in spring, but July and August are the driest months at all the stations. The Eastern Rocky Mountain Foothills type is sharply separated from the North Plateau type by the Rocky Mountain barrier. The seasonal variation of rainfall is by no means so marked as it is west of the Sierra Nevada-Cascade barrier. These winter rains or snows of the North Plateau type are brought by the general cyclonic storms of the colder months, the moisture coming very largely from the

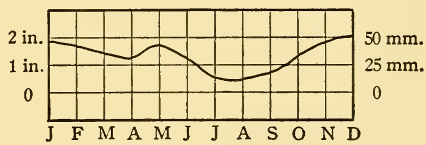

FIG. 67. North Plateau Type
Mean annual rainfall, 10–20 inches

Pacific Ocean. The spring and summer rains are mostly of local convectional origin. This North Plateau type of rainfall overlaps somewhat the southern boundary of the Northern Plateau climatic province, being found, as indicated on the map (Fig. 56), in northern Utah and in northern and northwestern Nevada. A few stations in the belt of country fringing the mountains in western Nevada share in the Pacific type of rainfall (see below), which here overlaps the Sierra Nevada from the west. The spring rains of Fig. 67 are economically of much importance, either directly, because they fall when the crops are making their early growth, or indirectly, because they are applied through irrigation. As Briggs and Belz have pointed out, spring wheat is not successful over much of this region because sowing cannot begin until late on account of the spring rains.[1] Fall-sown wheat, on the other hand, has the benefit of the winter and spring rains and matures before the dry season of July and August. There is so little chance of rain during the "dry" months that grain is often left for days in the open air, piled in sacks, before being taken to storage. The winter snows on the mountains are economically important in maintaining the summer flow of the rivers, which otherwise, in the summer dry season of this province, would have little or no water.

Going southward from the Northern Plateau Province into central and southern Nevada and Utah a gradual change takes place in the rainfall type. In place of the late-spring maximum of the North Plateau type, there is a more and more marked late-summer (July–August) maximum, with a secondary maximum in winter. The primary minimum comes in spring and early summer (May–June), the secondary minimum in autumn (October–November). Fig. 68 illustrates the *South Plateau* type. This is a complex curve. It shares in the characteristics of the New Mexican on the east and of the rainfall distribution of the Pacific slope on the west. It is on the whole most clearly developed in Arizona, but is found, often with more or less complication, over most of the Southern Plateau Province, in-

[1] L. J. Briggs and J. O. Belz, "Dry Farming in Relation to Rainfall and Evaporation," *U. S. Bur. of Plant Industry Bull. No. 188*, 1910.

cluding western Colorado and southeastern California. On the higher summits and slopes of the Colorado mountains most of the precipitation occurs in the colder months. States like Nevada and Utah, situated among three or four different rainfall types, naturally show considerable diversity and complexity in their rainfall types.[1] In the South Plateau type, one third or more of the annual rainfall comes in the months of July and August. The rainy season begins very suddenly, but there is a slow and moderate decrease toward the autumn minimum. The summer rains, which are very persistent, are afternoon or evening thundershowers of local convectional origin, occurring chiefly over the heated mountains and plateaus of this region, but also overlapping to some extent the adjacent valleys and plains. There is considerable variation in the annual amount of these rains. This fact suggests some more or less direct cyclonic control which is probably to be found in the permanent "Yuma low" over the lower Colorado. Water vapor from the Gulf of California is brought by the prevailing southerly winds on the eastern side of this low and is condensed as rainfall over the higher elevations. Weak secondary cyclonic depressions, moving eastward from the Yuma low, also seem to contribute a share of this summer rainfall. It is not improbable that the supply of water vapor from the Pacific Ocean is greater in summer than in winter, because the westerly winds are not likely to deposit as much moisture during their passage across the Sierra Nevada in the warmer season. The winter rains are cyclonic. They are more or less sporadic like the summer rains, occur in connection with low pressure areas, are under the same general control as the

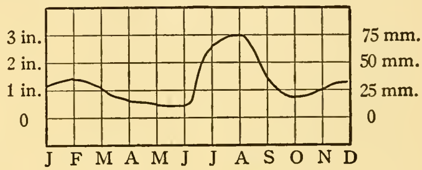

FIG. 68. South Plateau Type
Mean annual rainfall, 10–15 inches

[1] See, for example, Cleve Hallenbeck, "Summer Types of Rainfall in Upper Pecos Valley," *M. W. R.*, Vol. 45 (1917), pp. 209–216; J. C. Alter, "Normal Precipitation in Utah," ibid., Vol. 47 (1919), pp. 633–636; E. A. Beals, "The Semipermanent Arizona Low," ibid., Vol. 50 (1922), pp. 341–345 (discussion, pp. 345–347).

winter rains of the Pacific coast, and depend for their intensity, amount, and distribution upon the character, development, and movement of the winter cyclones. The principal rainy season of the South Plateau type comes after the time of maturity of the staple crops, which are here dependent upon irrigation. The cold-season rains help winter pasturage, and the winter snows, where they fall, protect the grass. The snow which forms much of the winter precipitation on the higher mountains is important in maintaining a supply of water for irrigation in the interval before the late-summer rains come.

Rainfall Types of the Pacific Province. The Pacific Province has well-marked winter rains, with wholly or relatively dry summers. The rainy season usually extends from October or November to March or April. Over much of the area more than half the annual rainfall comes in the period from December to February. The rainiest month is generally December. At some southern stations it is February. Light rains from weak cyclonic depressions keep the warmest months from being absolutely dry in northern sections. Farther south, while local thunderstorms occur on the mountains in summer, the lower slopes and valleys are practically or altogether rainless. Both lowlands and mountain slopes are warm and cannot cool the winds to the stage of precipitation as they do in winter. The length and intensity of the dry season increase from north to south. In the San Joaquin valley, for example, three or four months may be rainless. The rains of the southern Pacific coast, known as sub-tropical rains, were first observed and studied in the classic Mediterranean region of the Old World. Later they were found, with similar characteristics, in Chile and in southwestern Australia and South Africa, as well as on the Pacific coast of the United States in California. The control of these sub-tropical rains is intimately associated with the equatorward migration of the cyclonic storm belt of the prevailing westerlies with the advance of autumn and winter, and the poleward migration of this same belt in spring and summer. During the summer the coast is dominated by the high pressure belt of the North Pacific, with generally clear skies and conditions unfavorable to rainfall.

For convenience the state boundary between Oregon and California may be taken as the line roughly separating the two types of Pacific rainfall, although northernmost California is in general similar in its rainfall type to Oregon and Washington. To the north there is the *North Pacific* type (Fig. 69), with significant summer rains; to the south there is the *South Pacific* type (Fig. 70), extending over five hundred miles or more along the coast, with wholly or practically rainless summers except for occasional convectional showers on the mountains or in the upper valleys. The dry summer is of essential economic importance in making it possible to leave harvested cereal crops outdoors, uncovered, during their removal to more permanent storage places, and in providing an unusually favorable opportunity for sun-drying fruits like raisins and apricots. On the other hand, the precipitation of the colder months furnishes moisture for the fall-sown crops, which grow slowly through the winter months and are ready for harvesting at the end of the rainy season. The winter is the season when vegetation is green and fresh. In summer the landscape is brown and gray except where there is irrigation. The snowfall on the higher mountains provides the water necessary for irrigation when the winter rains are over. Afternoon thundershowers and occasional light rains occur in some summers. In California the rains of April and May are of the greatest value

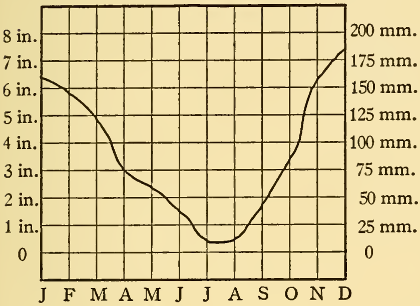

FIG. 69. North Pacific Type
Mean annual rainfall, 40–50 inches

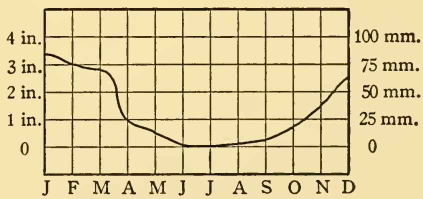

FIG. 70. South Pacific Type
Mean annual rainfall, 10–15 inches

to agriculturists. No matter how abundant the winter precipitation may be, it is the rains of April and May which are the critical ones.

Rainy Seasons. It is clear from an examination of the foregoing curves that certain portions of the United States have distinct rainy seasons. Such rainfall types as the Missouri, the Florida, the New Mexican, the Pacific, in which there is a well-marked variation in the rainfall during the year, have rainy seasons. On the other hand, obviously, the Ohio, the Tennessee, and, above all, the New England types have so uniform a distribution of rainfall that to speak of rainy seasons is out of the question. The percentage of the annual precipitation which falls in one season of the year is a fair indication of the occurrence or otherwise of what may be termed a rainy season. In winter the area having the highest percentages of the annual (40–60 per cent) is the Pacific coast, whose rainy season is well known and is commonly so termed. In spring the northern Rocky Mountain and Eastern Foothills region has the closest approach to a rainy season (30–35 per cent), but the excess of precipitation at that time is distinctly less marked than it is on the Pacific coast in winter. The area of fairly high spring percentages (over 30 per cent) stretches westward into Idaho and Nevada and eastward well onto the Plains. In summer the rainy season (40–50 per cent) is located still farther east: over the Plains and somewhat east of them, and in Florida. There is thus seen to be a seasonal migration of the area of relatively marked seasonal precipitation from the Pacific coast eastward to the Plains between winter and summer, corresponding to the seasons of maximum and of minimum marine controls and continental controls.[1] The only district with over 35 per cent of its annual rainfall coming in autumn is the southeastern coast of Florida. Taking the six warmer months together (April 1–September 30) it appears that the percentages of the annual precipitation falling in that half-year are highest (over 70 per cent) over most of the great agricultural region of the eastern United States, including the greater part of the Plains

[1] See Precipitation and Humidity section, *Atlas of American Agriculture,* Figs. 21, 31, 41, 51.

and the Prairie states.[1] This fact emphasizes the immense agricultural importance of the Missouri type of rainfall, with its late spring and early summer maximum.

Monthly and Seasonal Rainfall Maps: General. The preceding study of rainfall types brings out the essential facts regarding the distribution of rainfall throughout the year at the different groups of stations whose rainfall data were selected as the basis for the composite curves. The next step is naturally a consideration of the geographical distribution of rainfall over the United States as a whole, by months and by seasons.

In studying any series of monthly and seasonal rainfall maps it is important to remember that no single chart represents a fixed condition. Each shows a transitional stage between the rainfall of the preceding and that of the following map. The most vivid conception of the distribution of the rainfall throughout the year, as well as the most accurate one, is gained by viewing the successive maps as if they were a set of stereopticon pictures. Each picture develops out of the preceding one and dissolves into that which follows. The best way to gain this view is to hang the whole series of maps on a rack, or, if the maps are of small size, to have them all printed or mounted on one sheet. It is by no means difficult to familiarize oneself with the essential characteristics of each month's rainfall. The outstanding features may easily be re-

[1] Ibid., Figs. 3 and 4. Fig. 4 shows the period of the year during which 50 per cent of the annual precipitation occurs. Eshleman is of the opinion that the Great Lakes cause some diminution in the rainfall along their shores during the crop-growing season. He attributes this fact to the lake breezes, which check the ascending currents needed for the development of local thunderstorms. (C. H. Eshleman, "Do the Great Lakes diminish Rainfall in the Crop-Growing Season?" *M. W. R.*, Vol. 49 (1921), pp. 500–502.) For an earlier discussion of rainy seasons see M. W. Harrington, loc. cit. (Chart 20 and pp. 24–25 concern rainy seasons). The four seasonal charts in *Bull. C* are combined into one chart in the *Atlas of Meteorology*, Plate 19, text page 19. Harrington also indicated the location of the maxima and the minima of rainfall by means of lines drawn centrally through areas where a maximum or a minimum occurs in any month. The most noteworthy facts are the enormous area east of the Rocky Mountains with a June maximum, the extension of the winter maximum from the Pacific slope inland and eastward over the Plateau, and the greater extension of the minimum rainfall in winter than at any other season (loc. cit., Charts 19, 21). The area of maximum rainfall by months has been briefly discussed by Kincer, Precipitation and Humidity section, *Atlas of American Agriculture*, p. 37.

membered if the types and the chief controls of rainfall are held in mind. For ordinary purposes, in any general study of climatology, only the more important features of the seasonal and monthly rainfalls need consideration. Details may readily be secured, when needed, from the official publications of the Weather Bureau.

In a general survey of rainfall distribution throughout the year the seasonal maps may best be taken as the basis of study. They show the larger facts. They cover divisions of the year which are universally recognized as logical and as having human and economic significance. Further, they sufficiently emphasize the essential characteristics of the varying rainfall in different parts of the year without the risk of the confusion which is not unlikely to result from a detailed study of the twelve monthly maps. The latter should, however, by no means be discarded.

Several sets of monthly and seasonal rainfall maps of the United States have been published.[1] There are certain fundamental objections to them: (1) the number of stations for which data were available was limited; (2) the records did not

[1] Lorin Blodget, "Climatology of the United States and of the Temperate Latitudes of the North American Continent," 1857 (rainfall maps for the year and the seasons).

H. H. C. Dunwoody, "Charts and Tables showing Geographical Distribution of Rainfall in the United States," *U. S. Signal Service Professional Paper No. 9*, 1883 (monthly and annual charts).

H. H. C. Dunwoody, "Normal Monthly Rainfall throughout the United States, based upon 18-Year Normals, accompanied by a General Description of the Rainfall of the United States," *U. S. Signal Service*, 1889.

A. W. Greely, "American Weather," 1888 (Charts XIII–XV; average rainfall for April, May, and June, based on observations for eighteen years).

M. W. Harrington, "Rainfall and Snow of the United States, compiled to the End of 1891, with Annual, Seasonal, Monthly, and Other Charts," *U. S. Weather Bur. Bull. C*, 1894, Atlas and Text (the monthly maps are reproduced on a small scale in *Atlas of Meteorology* (1899), Plate 24; text pages 24–25. The isohyetal lines have been extended into Canada and Mexico).

A. J. Henry, "Rainfall of the United States, with Annual, Seasonal, and Other Charts," *U. S. Weather Bur. Bull. D*, 1897 (charts of mean annual rainfall for the United States as a whole and for the eastern United States for April–September).

J. B. Kincer, "The Seasonal Distribution of Precipitation and its Frequency and Intensity in the United States," *M. W. R.*, Vol. 47 (1919), pp. 624–631 (charts and figs.).

C. A. Schott, "Tables and Results of the Precipitation, in Rain and Snow, in the United States; and at Some Stations in Adjacent Parts of North America, and

cover a uniform period and were not reduced to a uniform period; (3) the isohyetal lines were generally drawn with little or no regard to topographic controls. For the climatic section of the *Atlas of American Agriculture* a wholly new set of monthly and seasonal charts was constructed.[1] These new charts mark a very decided advance over all the earlier ones and will for years remain the standard series. They are based on a large number of records (3600). The stations are well distributed over the country. The records were all reduced to the uniform period of twenty years, from 1895 to 1914, about 1600 cases being actual averages for this period (short breaks being interpolated), and the remaining 2000 having been reduced to this same period. Further, the isohyetal lines were drawn on hachured base maps, and in locating the lines reasonable attention was paid to topographic controls. Isohyets are drawn for 0.5 in., and then for every inch or for greater intervals in cases where the lines are crowded.

The accompanying charts (Figs. 71–74) show the mean average precipitation over the United States for the four seasons, and summarize in a convenient way the essential facts regarding the distribution of precipitation throughout the year.

in Central and South America," *Smithson. Contr. to Knowl.*, Vol. 18, *No. 222* (1872), pp. 1–175 (rainfall maps for summer, winter, and year); 2d ed., ibid., Vol. 24, *No. 353* (1881), pp. i-xx, 1–249 (charts for year and for four seasons).

B. C. Wallis, "The Rainfall of the Northeastern United States," "The Distribution of the Rainfall in the Eastern United States," "The Distribution of the Rainfall in the Western United States," "The Rainfall Régime of the Several States," and "Rainfall and Agriculture in the United States," *M. W. R.*, Vol. 43 (1915), pp. 11–24, 170–178, 267–274. (In this series of papers Wallis presents charts showing the rainfalls for each month by lines of equal departure from the rainfall norm, or "equipluves." The norm is the amount of rainfall that would occur at any place on the assumption that such rainfall is evenly distributed throughout the year. In other words, the usual monthly rainfall averages are expressed as percentages of the annual value at each station. Charts of the wettest and driest months and of rainfall regions are given, as well as diagrams of rainfall intensities.)

B. C. Wallis, "Rainfall and Raininess," *M. W. R.*, Vol. 46 (1918), pp. 229–230 (gives diagrams showing how to convert "equipluves" into isohyets; that is, raininess into rainfall, and vice versa).

Climatic Charts of the United States, *U. S. Weather Bur.*, 1904.

[1] Precipitation and Humidity section, Figs. 18, 19, 23, 28, 29, 33, 38, 39, 43, 48, 49, 53 (monthly maps); Figs. 20, 30, 40, 50 (seasonal maps). Figs. 71–74 below were redrawn, with some modifications and a few omissions, from the four seasonal maps in the *Atlas*.

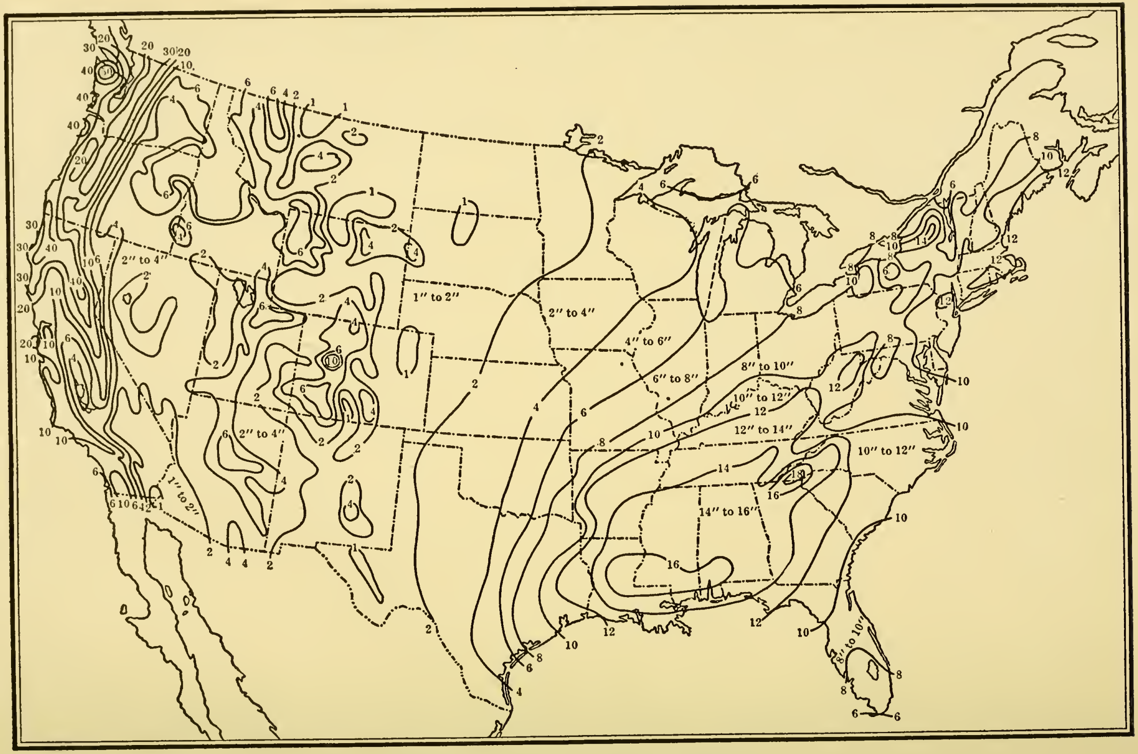

FIG. 71. Average Winter Rainfall

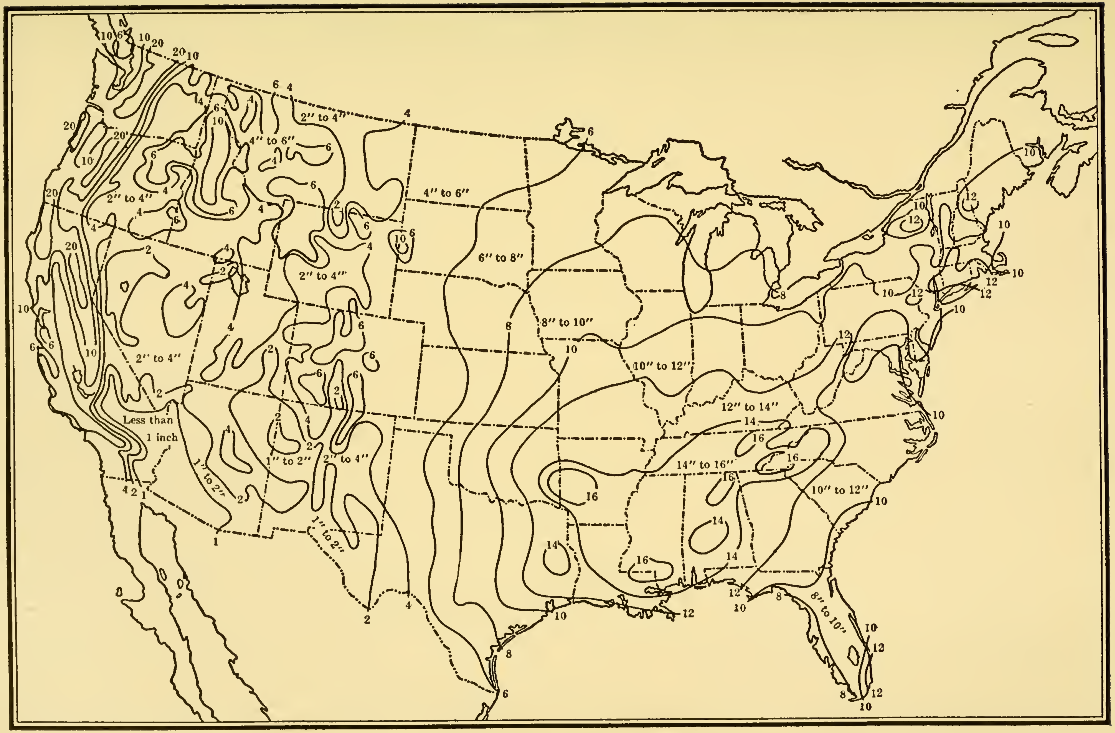

FIG. 72. Average Spring Rainfall

The Larger Facts brought out on the Charts. A general glance at the maps brings out three striking facts: (1) On the Pacific coast there is a well-defined seasonal migration, northward and southward, of a zone of rainfall which in some months may be considered to overlap the Sierra Nevada-Cascade barrier and expand over the northern and southern Plateau areas. These rain conditions are associated with the poleward and equatorward migration of the storm belt, as well as with seasonal changes in temperature over the land which offer the best opportunities for condensation in winter. (2) Over an extended area between the Rocky Mountains and the Mississippi River the rainfall lines advance northward and westward in spring and early summer and retreat southward and eastward in late summer and autumn. That is, the conditions favorable for heavier rainfalls move from the Gulf of Mexico up the Mississippi Valley and out over the Plains and then back again. These fluctuations are associated with the development, as the continent warms, of a system of inflowing warm winds carrying abundant moisture, and with the gradual replacement of this régime, as the continent cools, by a system of outflowing winds. (3) The eastern half of the country shows less difference between the rainfalls in the several months than the western. The districts of greatest fluctuation are along the southern Atlantic and Gulf coasts. In the eastern sections the decreased cyclonic rainfall of the warmer months is largely or wholly compensated by frequent summer thunderstorms, while along the southern coasts West Indian hurricanes give heavy though more or less local and irregular downpours in the late summer and autumn months.

Seasonal Rainfall on the Pacific Coast. The seasonal fluctuation in rainfall on the Pacific slope is, on the whole, the most striking feature on the charts. When the four seasonal charts are examined in their logical order, the winter maximum is seen to grade through a spring with decreasing rainfall to a summer minimum. Autumn follows with a general increase over the whole slope. This is the type of rainfall known as the Pacific. The topographic influences upon the seasonal amounts stand out with remarkable distinctness. In winter

considerable portions of the Cascade and Sierra Nevada mountains have over 30 in. The northern portion of the Coast Range locally has over 40 in., with over 50 in. on Mt. Olympus, on the extreme northwestern coast of Washington. The valleys and lowlands have distinctly less rainfall. In Washington and Oregon most of the lower land is inclosed by the 20-inch line. Farther south the great valley of California averages below 20 in.; much of it has less than 10 in., and the southern portion even less than 5 in. On the immediate seacoast the winter rainfall decreases from north to south from 30–40 in. to less than 6 in. Summer is the driest season. The maximum rainfalls on the mountains are nowhere 10 in., even in the north, while the valleys have roughly from 2 to 4 in. in the north and under 0.1 in. in the southern portion of the great valley of California. Spring and autumn are intermediate seasons and have intermediate amounts of rainfall.

This marked seasonal migration, poleward and equatorward, of the rainfall conditions on the Pacific coast is still better illustrated on the monthly charts. From March to July and August there is a striking and interesting withdrawal up the coast of the zone of winter rains, dependent upon the northward retreat of the storm belt and upon the gradual warming of the land. By April the maximum monthly rainfall on the coast in the extreme northwest is 6–10 in.; 1–2 in. occur in the region about San Francisco and 0.5 in. on the southern coast. The 1-inch line on the coast is slightly north of San Francisco in May; in June it is on the northwestern California coast. The July map shows the minimum of the Pacific type; that is, the extreme northward migration of the winter rains. Only a small area in the northwest and the upper slopes of the Cascade Mountains have rainfalls of more than 1 in. From August through to December the belt of winter rains is moving southward again. Each month shows an extension of the area covered and an increase in the amount of precipitation. Thus, for the central California coast, around San Francisco, this monthly increase is clearly indicated by the following amounts of rainfall: August, a trace; September, 0.5–1 in.; October, 1–2 in.; November, 2–3 in.; December, about 3 in.

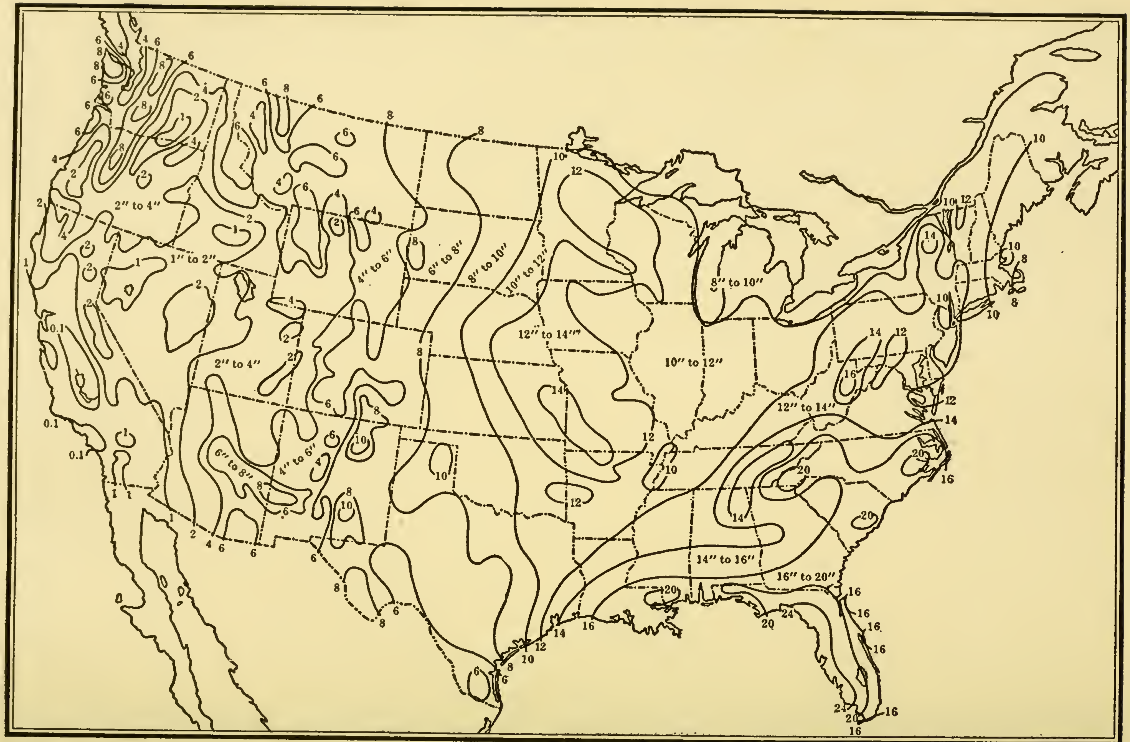

FIG. 73. Average Summer Rainfall

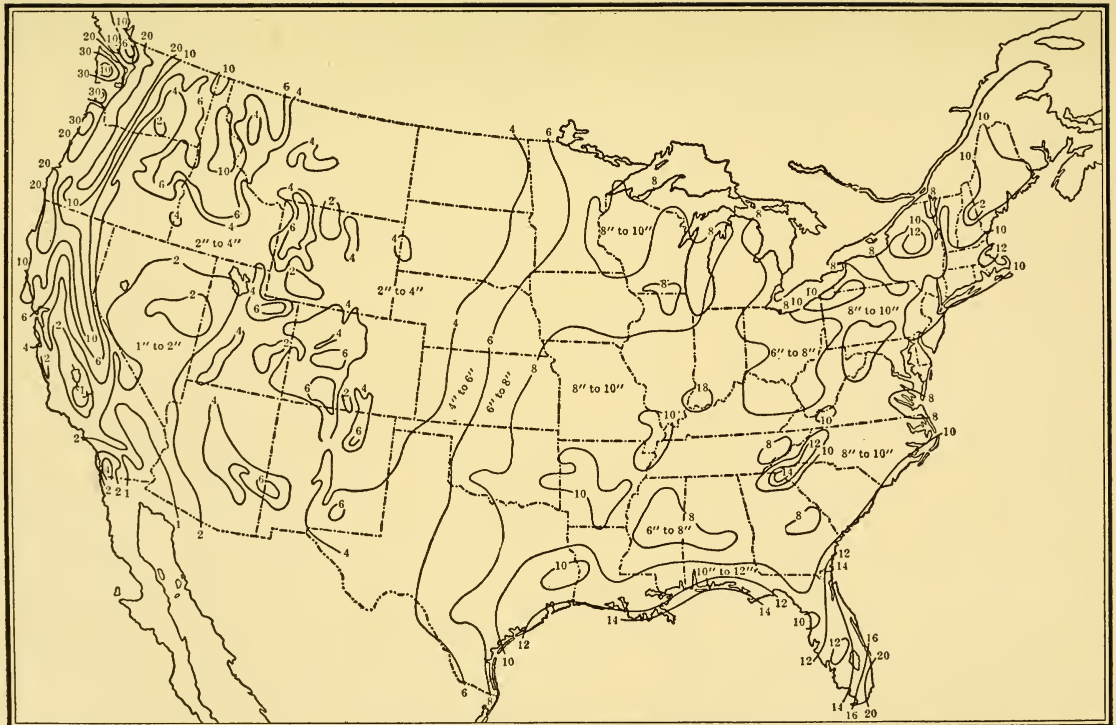

FIG. 74. Average Autumn Rainfall

Seasonal Rainfall in the Plateau Province. The Plateau Province lies in the rain-shadow of the Cascade-Sierra Nevada ranges. Its seasonal rainfall has both marine and continental characteristics. The cold-season rainfall of the Pacific coast may be considered as extending across the mountains into the western portion of the Plateau, causing the primary or secondary winter and early spring maxima of this interior district, these rains being heavier in the north, where there is the greatest cyclonic activity (Northern Plateau type). Over the northern plateaus the seasonal amounts decrease from winter to summer, both on the mountains and also over the lower portions of the district. The southern Plateau has its driest seasons in autumn and spring, with the primary maximum in summer (Southern Plateau type). As illustrating these points, the following broadly generalized seasonal rainfall amounts for different parts of the Plateau Province are given:

SEASONAL RAINFALL IN THE PLATEAU PROVINCE

Season	Northern Plateau		Southern Plateau	
	Lower Altitudes	Mountains (Eastern)	Lower Altitudes	Mountains
Winter	About 4″	6″–10″+	1″–4″	4″–6″
Spring	< 2″–4″	6″–10″+	< 1″–2″	2″–4″+
Summer	< 2″–4″	4″–6″+	< 1″–4″	6″–8″+
Autumn	2″–4″	6″–10″+	< 1″–4″	4″+

Seasonal Rainfall over the Plains. The second striking feature on the charts concerns the seasonal fluctuations of rainfall over the Great Plains. In winter the 100th meridian marks about the average western limit of a seasonal rainfall of 2 in. for the eastern United States. In the north the 2-inch line is well east of the Plains, reaching central Minnesota; in Texas there is a slight extension to the west of the 100th meridian; the 2-inch line crosses the meridian in Kansas. From month to month, as spring advances, the rainfall lines over the great central lowlands move northward and westward from the Gulf of

Mexico. The conditions favorable for increasing rainfall progress inland as the gradual heating of the continent develops a system of inflowing, damp winds which, in a sense, carry the rainfall lines with them. In March the 1-inch line is about on the 100th meridian; in April the 2-inch line and in May the 3-inch line occupy roughly this same position. The spring map shows that the rainfall along the eastern margin of the Plains has increased to three times that of winter (6 in. as against 2 in.). This westward migration is at its maximum in June, when there are monthly rainfalls of more than 3 in. over considerable portions of the eastern and northern Great Plains. The charts thus indicate very clearly the progress of conditions which give the spring and early summer maxima of the Eastern Rocky Mountain Foothills and Missouri rainfall types. The pronounced northwestward extension of these rainfall maxima appears in the trend of the rainfall lines in June.

In July the swing of the sun southward after the summer solstice, and the passing of the conditions which gave the early summer maxima, result in a retreat of the rainfall lines eastward across the Plains. This retreat is greatest and most rapid in the north, where the westward advance was the greatest. In the south, between June and July, instead of a retreat there is a distinct extension westward, over New Mexico and Arizona, of rainfall conditions of 2–4 in. This is the map evidence of the approach of the late summer maximum, due essentially to local convectional rainfalls of the New Mexican and Southern Plateau types. The general eastward withdrawal of the rainfall lines over the Plains continues month by month until winter. The seasonal rainfall amounts along the eastern margin of the Plains are as follows: winter, 2 in.; spring, 6 in.; summer, 8–10 in.; autumn, 4 in. in the north to 6 in. in Texas. This great seasonal migration of rainfall conditions over the area west of the Mississippi River, over the Great Plains, brings to mind the economic importance of the warm-season rains in that region. The approach of the time of rainfall maximum is anxiously awaited by the farmers. Upon the proper distribution of the rain, in time and in amount, depends the success of agricultural operations over vast areas of these states.

Seasonal Rainfall in the Eastern and Gulf Provinces. The third large fact illustrated by the charts concerns the rainfall of the eastern United States. It is apparent that, on the whole, the distribution of rainfall throughout the year is generally more uniform in the east than in the west, although there are certain sections of the country east of the Plains where the seasonal fluctuation is well marked. Thus, the westward migration of the rainfall lines in spring and summer, referred to in the preceding paragraphs, is a striking characteristic of the Mississippi-Missouri Valley region. Other seasonal fluctuations shown on the charts are (1) the winter and (early) spring rainfalls of the Tennessee type, followed by a drier summer and autumn, and (2) the marked (late) summer and (early) autumn rainfalls along the Gulf and southern Atlantic coasts (Atlantic, Florida, North Gulf Coast, and Texas types). The generalized seasonal amounts of rain along the Gulf coast are as follows:

Seasonal Rainfall along the Gulf Coast

Season	Florida	Louisiana	Texas
Winter	6″–14″	12″–14″	4″–12″
Spring	8″–14″	12″–14″	6″–12″
Summer . . .	16″–24″	16″+	6″–14″
Autumn . . .	12″–20″	12″–14″	8″–12″+

General Seasonal Distribution of Precipitation. A comparison of all the charts shows a general decrease over the eastern United States as a whole from the warmer to the colder months. Autumn is generally the driest season. It further appears that the rainfall charts for the summer months resemble the mean annual rainfall map somewhat more closely than do the charts for the winter months. The warm-season rains, therefore, are the dominant control in eastern sections. The continental type of late spring, summer, and early autumn rainfalls covers a larger area and is more important than the cold-season rains. For the United States as a whole the rainfall of summer is the

heaviest; then that of spring, with winter third, and autumn the driest season. The dominance of the continental type of warm-season rains is thus clearly brought out. Roughly, over the eastern two thirds of the country the rainfall of the crop-growing season, so called, from April to and including September, is the most critical in agricultural operations.[1] Grains sown in autumn make practically no progress during the winter, but grow rapidly in spring. To the west of the Rocky Mountains, on the other hand, the precipitation of the winter is the most important, both directly and also because of its use for irrigating later in the season. Fall-sown grains grow during the winter over most of the Pacific coast and mature after the rainy season is over.

[1] Fig. 8, Precipitation and Humidity section, *Atlas of American Agriculture,* shows the average warm-season precipitation (April to September inclusive).

CHAPTER X

SOME CHARACTERISTICS OF RAINFALL

ANNUAL AND MONTHLY VARIABILITY OF RAINFALL · NUMBER OF RAINY DAYS · PROBABILITY OF RAIN · CONSECUTIVE DAYS WITH AND WITHOUT PRECIPITATION · DROUGHTS · HOURLY FREQUENCY OF RAINFALL: DAY AND NIGHT RAINFALL · HEAVY RAINFALLS IN SHORT PERIODS · SECULAR VARIATIONS IN RAINFALL: INSTRUMENTAL RECORDS · SECULAR VARIATIONS IN RAINFALL: NON-INSTRUMENTAL EVIDENCE · THE CONSERVATIVE ATTITUDE REGARDING NON-INSTRUMENTAL EVIDENCE OF CLIMATIC CHANGES

Annual and Monthly Variability of Rainfall. The amount of precipitation which occurs in a year is variable, because the rain-producing conditions, such as the number, intensity, and paths of cyclones, and the general pressure distribution, vary more or less from year to year. A close study of the daily weather maps usually shows why a given station or district had a wetter or a drier year than normal. It is important for many persons, notably farmers and engineers, to be informed concerning the probable limits of such variations. It matters little to the farmer to know that the *mean* or *average* rainfall over his section is sufficient for the growth of a large crop if in some seasons his fields are parched during an unusually dry time and in others his crops suffer from excessive rains. He needs to know what departures from the average he may expect in the run of the years. He is then in a far better position to decide what crops he may plant with the greatest probability of success. The following generalized table, prepared by Henry some thirty years ago, shows the ratios of the rainfalls of the wettest and driest years to the mean annual rainfalls for selected stations throughout the United States:[1]

[1] A. J. Henry, "Rainfall of the United States, with Annual, Seasonal, and Other Charts," *U. S. Weather Bur. Bull. D* (1897), p. 41.

RATIO OF WETTEST AND DRIEST YEARS TO THE MEAN RAINFALL

MEAN RAINFALL	AVERAGE OF WETTEST YEAR	AVERAGE OF DRIEST YEAR
Inches	*Per Cent*	*Per Cent*
50–60	142	70
40–50	143	64
30–40	154	64
5–30	178	55

To state these relations verbally: an annual rainfall of nearly 180 per cent of the mean may be expected in districts with mean annual rainfalls of 5–30 inches. In these same districts the rainfall of the driest years averages only slightly over half the mean. It will be observed that the departures from the mean average greater where the annual amounts are smaller.[1] Furthermore, there may be a succession of several years with an excess or a deficiency. During 1869–1903, considered by five-year periods, a total of 119 stations in the "arid region" showed an excess in average annual rainfall, and 150 showed a deficiency.[2] It appears to be a general rule that years with precipitation above the mean are slightly less frequent than those with precipitation below the mean. The plus departures are therefore a little greater than the minus departures.[3]

Remarkable cases of great differences between the rainfalls of consecutive years are on record. Thus, on Mt. Hamilton, California, 90.1 in. of rain and melted snow were measured in 1884 and only 18.4 in. in 1885.[4] Many illustrations, although few as striking as this one, may be found in the records of the Weather Bureau. The rainfall of any individual month may

[1] See also A. R. Binnie, "On Mean or Average Annual Rainfall and the Fluctuations to which it is Subject," *Proc. Inst. Civ. Eng.*, Vol. 109 (1891–1892), Part III, London, 1892. The average limits for wettest and driest years in North America are 141 per cent and 68 per cent as quoted by Hann, "Lehrbuch der Meteorologie" (3d ed.), p. 332.

[2] W. B. Stockman, "Periodic Variation of Rainfall in the Arid Region," *U. S. Weather Bur. Bull. N* (1905), p. 6.

[3] An earlier table showing the mean annual deviation of rainfall at selected stations in the United States, as determined by Blanford's method, will be found in A. W. Greely's "American Weather" (1888), p. 154.

[4] A. J. Henry, *Bull. D*, p. 23.

also differ greatly from the normal of that month. In a certain September, for example, when three cyclonic centers passed over the south Atlantic states, the average rainfall for that district was 9.47 in., whereas in the same month in another year, when no storm center crossed the region, the average rainfall was less than one fifth (1.84 in.) as large.[1] It is always instructive to investigate the weather map conditions which give rise to unusually wet or dry months. The prevailing winds and the pressure distribution during a wet and during a dry winter month on the Pacific coast have been charted by Henry.[2] The abnormally rainy month was clearly due to the displacement, to the south of their usual latitudes, of the tracks of the low pressure areas. The amounts of rainfall along the coast north of San Diego were in most places over twice the normal, and in the Colorado region, where the monthly mean is less than 2 in., this particular month gave over 10 in. Unusually heavy monthly rainfalls over the Plateau are almost always due to persisting cyclonic conditions west of the Rocky Mountains. In the dry month the tropical high pressure system was abnormally far to the north, and the rainfalls averaged about half the normal amount. The prevailing pressures and winds in a wet and a dry March in the Mississippi Valley have also similarly been considered by Henry, and McAdie has charted the typical pressure distribution and flow of winds during a wet and a dry winter month in California.[3] The former had low pressure over the northwestern coast, with prevailing southerly (that is, rainy) winds; the latter had high pressure over the northern Plateau, with prevailing northerly (that is, dry) winds.[4]

[1] A. W. Greely, "American Weather" (1888), p. 143.

[2] See A. J. Henry, "Rainfall of the United States, with Annual, Seasonal, and Other Charts," *U. S. Weather Bur. Bull. D* (1897), Charts IV, VI, VIII, X, pp. 23–24; *Atlas of Meteorology*, text page 35, Plate 33. See also A. J. Henry, "Seasonal Forecasting of Precipitation—Pacific Coast," *M. W. R.*, Vol. 49 (1921), pp. 213–219.

[3] A. G. McAdie, "The Rainfall of California," *Univ. of Cal. Publs. in Geogr.*, Vol. 1, No. 4 (February, 1914), Figs. 1–2, Plates 25–26, pp. 131–132.

[4] As the result of distinctly deficient precipitation in central and northern California during the four preceding rainy seasons, serious losses resulted in the dry season of 1920. Streams reached the lowest stages on record. The average yield per acre of many crops was reduced. Rice-growers felt the drought keenly

Kincer has studied the variations of precipitation annually, seasonally, and in individual months for a considerable number of stations in different parts of the United States for the period 1895–1914.[1] The variations in the annual amounts of precipitation are large on the Pacific slope, in the Gulf region, and over the Plains, and comparatively small in the region of the Mississippi and Ohio valleys.[2] Over the Great Plains the annual variations are somewhat smaller over the northern sections; in the south they are larger and therefore usually more critical. It is a generally recognized tendency for several years with fairly abundant rainfall to come in succession, and to be followed by a series of years with a deficient supply of moisture. While wetter and drier years thus tend to recur in groups, the succession is not regular and cannot be depended upon in planning agricultural undertakings. A series of wetter years tempts people to push out onto the more arid western Plains, there to try farming by ordinary methods. Then, when the drier years follow, as they are certain to do, crop failures and financial disaster are the natural result. During the years 1917–1919 the greatest accumulated deficiency of rainfall noted in fifty years of observations occurred over the northern Plains and was followed by serious financial losses and the closing of many local banks.

The variations from the average monthly precipitation are large on the Pacific coast. Over the east they are generally largest in the districts of heaviest annual rainfall and comparatively small from the Great Lakes eastward.[3]

because of the large water requirements of rice. Litigation over water rights ensued. Hydroelectric-power shortage resulted in power restrictions and higher rates for electricity. Wells went dry. Forest fires were more frequent and destructive than in past years (A. H. Palmer, "Economic Results of Deficient Precipitation in California," *M. W. R.*, Vol. 48 (1920), pp. 586–589). See also E. S. Nichols, "Frequencies of Monthly and Seasonal Rainfalls of Various Depths at San José, California," ibid., Vol. 51 (1923), pp. 459–462.

[1] See Precipitation and Humidity section of the *Atlas of American Agriculture*, Figs. 1, 5–7, 10–11, 15, 22, 32, 42, 52, 58–65. See also J. B. Kincer, "The Seasonal Distribution of Precipitation and its Frequency and Intensity in the United States," *M. W. R.*, Vol. 47 (1919), pp. 624–631, and "The Climate of the Great Plains as a Factor in their Utilization," *Annals Assoc. Amer. Geogr.*, Vol. 13, No. 2 (1923), pp. 67–80, especially pp. 70–73.

[2] Precipitation and Humidity section, *Atlas of American Agriculture*, Fig. 5.

[3] Ibid., Fig. 15.

It is well known that vegetation is, as a rule, more affected by a deficiency of moisture than by an excess. Hence the importance of knowing how often the precipitation in the growing season is likely to be below a certain critical value. In the vicinity of Yuma, Arizona, less than 85 per cent of the annual precipitation during the period 1895–1914 fell in half the years. On the other hand, more than 85 per cent of the annual mean fell in over 90 per cent of the years in parts of the lake region, of the Atlantic coast states, and of Tennessee.[1] The warm-season (April–September) rainfall was less than three fourths of the average in eight to eleven years in southern California and parts of the adjoining states, but fortunately for the great agricultural interests of the region east of the Rocky Mountains a warm-season precipitation of less than 75 per cent of the average occurred in only two to four seasons during that period.[2] For each of the eight months March to October the relative frequency of monthly precipitation less than half the average has been charted.[3] The practical value of these charts may be realized by an examination of the facts which appear on any one of them. Take, for example, July, a critical month for many of the great staple crops. It appears that in the central and eastern portions of the cotton belt there are a number of localities where only one July with a deficiency of more than half the average rainfall occurred in twenty years. At some points no year had a July rainfall of less than half the average. The country east of the Mississippi River as a whole had few deficiencies of 50 per cent. On the other hand, the percentages of frequency of a July precipitation less than half the average are large on the Pacific slope, especially in California.[4]

[1] Precipitation and Humidity section, *Atlas of American Agriculture*, Fig. 7.

[2] Ibid., Fig. 11.

[3] Ibid., Figs. 58–65.

[4] The fluctuations of the monthly rainfalls at New York during the period 1871–1900 have been investigated by Wachenheim. Three times in ten years a month occurs with less than 25 per cent of its mean, usually in September and October. About twice as often the rainfall of a month is over 200 per cent of the mean, mostly in summer and autumn. In 70 per cent of all months the amount of rainfall is less than 50 per cent above or below the normal. The annual means vary between 80 and 130 per cent of the normal. The mean annual variability is only 9 per cent (F. L. Wachenheim, "Die Hydrometeore des gemässigten Nordamerika," *Met. Zeitschr.*, Vol. 22 (1905), pp. 193–211).

Number of Rainy Days. The annual amount of rain or of snow is often of less economic interest than the frequency of the stormy days on which the precipitation comes. In some climates the total annual precipitation falls on comparatively few days, the rest of the year being rainless; in others, where the annual rainfall is smaller, the rains are well distributed, falling on many days throughout the year. Climates of the latter type may be much more favorable for crops than the former. The number of rainy days is thus often a more critical factor in the growth of vegetation and in many of man's outdoor activities than the annual amount of precipitation.

Fig. 75 shows the average annual number of "rainy days," that is, days with measurable precipitation (0.01 in. or more), in the United States. It is much simplified and generalized from the latest map published by the Weather Bureau.[1] Several lines and certain small areas of local rather than general interest have been omitted, many of the lines have been "smoothed," and shading has been used for purposes of emphasis. Such broad generalizations are perfectly legitimate in studying the larger characteristics of the climates of an extended area.

Summarizing the facts briefly, it is seen that over the eastern part of the country the average number of rainy days exceeds 100 a year; over the western, with the exception of the north Pacific coast and a few local areas not shown on the map, rain falls on less than 100 days. From the 95th meridian eastward there is an increase in the number of rainy days toward the Atlantic Ocean and especially toward the Great Lakes (maximum of 170). From the 95th meridian westward there is a general decrease except on the north Pacific coast, where there is a maximum of 180 rainy days. The distribution of rainy days here shown finds its explanation (1) in the cyclonic control over precipitation, (2) in the mean annual rainfall, and (3) in the distribution of rainfall through the year. The eastern maximum in the Great Lakes region, where the annual amount of precipitation is not large, results from the frequency of

[1] Average Annual Number of Days with Precipitation 0.01 Inch or More. Map, 16 x 10 inches. *U. S. Weather Bur.* One of a set of Climatic Charts of the United States.

cyclonic rainfalls throughout the year and from the local effects of the lake waters. The local excess of rainy days at the eastern end of Lake Erie (Buffalo, New York) is largely due to the frequent occurrence of snowfalls when the winds are off the lake in the colder months. On the Pacific coast, where there is a well-marked rainy season, the number of rainy days is closely related to the annual amounts of rainfall, the number

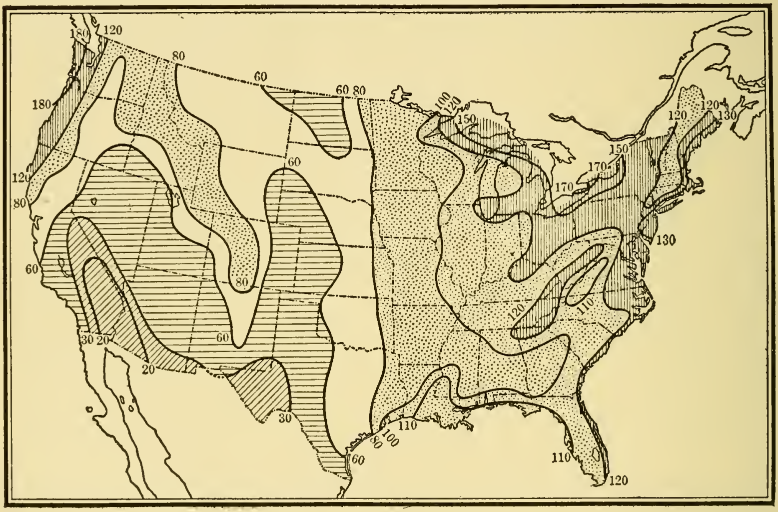

FIG. 75. Average Annual Number of Rainy Days

of rainy days being largest where the rainfall is the heaviest. Rain falls on nearly half the days of the year on the extreme northwestern coast. Here, as also in the case of the Great Lakes, a position to leeward of an immediate source of water vapor increases the number of rainy days. The northern tier of states, from the Pacific across to the Atlantic, is the pathway most frequented by a more or less continuous succession of rain-bringing cyclones. These northern states therefore have, on the whole, more rainy days than their neighbors to the south. From north to south, on the Pacific slope, the decrease in number of rainy days is very marked, as is also the decrease in mean annual rainfall and cyclonic activity. The minimum

number of rainy days in the country is found in the southwestern portion of the Southern Plateau Province. Here also are the smallest rainfall, the minimum of storm control, and a very effective inclosure from moisture supply. Southern California is seen to be favored, from the point of view of an outdoor life, in having so few rainy days. Many topographic controls over the number of rainy days are indicated on the map, and several others have been omitted. Frequent rains or snowfalls will naturally occur on the windward slopes of mountains. The effects of the Rocky Mountains stand out clearly. Local topographic effects (not shown on Fig. 75) are a district over the Arizona plateaus, including Grand Canyon station and Flagstaff, with more than 60 rainy days; and areas with more than 100 rainy days (1) in northern Idaho and eastern Washington and Oregon, (2) over the Yellowstone National Park, and (3) in western Colorado. An interesting local area of less than 30 rainy days a year, not shown, centers in southeastern Utah over the Colorado River valley. In the east the effect of the Appalachians is shown, especially in latitudes 35° to 40°. The interior of New England has fewer rainy days than either its coast or its western margin. Several small local areas have been omitted in the east, as has one larger district (over 110) extending along the Mississippi River from Memphis, Tennessee, to Dubuque, Iowa.

Of critical importance in agricultural operations are the frequency and intensity of precipitation. One section may have a good deal less rainfall in the course of a year than another; and yet the former, because of a better distribution and of a less torrential character of the rains, may offer more favorable conditions for agriculture. When the average numbers of rainy days are charted for the seasons and for the months a striking fact appears. In eastern sections, where the mean annual rainfall increases from north to south, the number of rainy days often increases from south to north, especially in spring.[1] In other words, rain falls at shorter intervals where the total annual amount is less, thus compensating to some

[1] Precipitation and Humidity section, *Atlas of American Agriculture,* Figs. 12, 24–27, 34–37, 44–47, 54–57; text pages 41–42.

extent for the smaller amount. However, the rule does not always hold. For example, the number of rainy days is small in the drier western section, whereas on the northern Pacific coast, where the annual amounts are large, the number of rainy days is also large. As a whole the amount of precipitation per rainy (or snowy) day is considerably greater in the rainier south than in the drier north and west, the contrast being most marked in the colder months.[1]

Probability of Rain. By dividing the average number of rainy days in a month or a year by the number of days in those periods, the mean monthly or mean annual *probability of rain* is determined. This value, expressed as a percentage, is a convenient and useful way of indicating the probability of occurrence of days with 0.01 in. or more of precipitation. In weather forecasting, in planning outdoor work or sports, in selecting a health resort, the probability of rainy days is of real human interest. A few years ago at a well-known university center the question came up of selecting a date for the performance of an open-air pageant. The available dates were the middle of May or some time early in June. It was important, among other things, to take into account the probability of rain during the two or three days of the pageant. At the place in question June has a smaller probability of rainy days than May and also has a smaller rainfall. June, therefore, other things being equal, was in the long run likely to be the better month for the performance.

In 1891 General A. W. Greely, then Chief Signal Officer, published a series of maps showing the probability of rainy days for each month.[2] No later monthly charts of rain prob-

[1] The average annual number of days with light rains (0.01–0.25 in.) is less than 20 in southeastern California and reaches 120 in the upper Lakes region and on the north Pacific coast (*Atlas*, Fig. 71). Days with moderate precipitation (0.26–1 in.) average less than 10 a year in parts of the southern Plateau region, but reach 50 on the north Pacific coast and over the central Appalachian Mountains (Fig. 72). Finally the most days (over 5 a year) with heavy rainfall (over 2 in.) occur in the central Gulf coast (Fig. 73). In the warm season (April–September) rain (0.01 in. or more) falls on the average on from 40 to 60 days over the principal agricultural districts east of the Rocky Mountains (Fig. 12).

[2] A. W. Greely, "Charts showing the Probability of Rainy Days, prepared from Observations for Eighteen Years," *U. S. Signal Service*, 1891.

ability have been published. In a broad climatological consideration the details of rain probability for each month are hardly necessary. The accompanying figure (Fig. 76) shows the mean annual probability of rain in the United States. It was prepared by the writer and is based upon the latest Weather Bureau chart of the average annual number of rainy days referred to above. The lines are somewhat generalized, and some unnecessary details, chiefly of local interest, are omitted.[1]

The extreme northwestern coast and the Great Lakes have the greatest probability of rain. Both of them are regions of marked cyclonic activity. One day in every two days is likely to be rainy on the coast of Washington. East of the Great Plains the probability of rain is more than 20 per cent. Over much of this area, especially toward the coast and the Great Lakes, it is over 30 per cent, and more than 35 per cent of all the days of the year are likely to be rainy over a considerable portion of the Great Lakes region and on the New England coast. The central Appalachians have a slightly higher rain probability than the surrounding lowlands,[2] while to leeward, chiefly in Virginia, there is a small area under 30 per cent.

With decreased cyclonic control and less favorable rainfall conditions, most of the vast area west of the 100th meridian and east of the Pacific slope mountains has less than 20 per cent, the rain probability being somewhat greater over the Rocky Mountains and decreasing to less than 5 per cent in the arid Southwest.[3] It is seen that the New England coast and much of the Great Lakes area have more than seven times as many rainy days as southwestern Arizona, and that the eastern margin of the Great Plains has half or less than half as many as the Oregon coast.

[1] M. W. Harrington, "Rainfall and Snow of the United States, compiled to the End of 1891, with Annual, Seasonal, and Monthly Charts," *U. S. Weather Bur. Bull. C*, 1894. Text and Atlas. References in Atlas, Sheet XXII, Charts 5–7; text pages 25–26 (three generalized charts of annual, greatest, and least probability of rain). Current data regarding the number of rainy days at Weather Bureau stations may be found in the monthly issues of *Climatological Data by Sections*, in the *Monthly Weather Review*, and in the *Annual Reports of the Chief of the Weather Bureau.*

[2] Not shown in Fig. 76.

[3] Several small areas having slightly higher or slightly lower percentages than their surroundings are omitted in order to simplify the map.

The seasons of greatest and of least probability of rain may easily be inferred from a knowledge of the seasonal distribution of rainfall in various sections of the country. The marked cyclonic activity of the colder months readily suggests that winter will bring the greatest probability of rain on the Pacific coast, over much of the western Plateau area, and in considerable sections in the East, heading up toward the Great Lakes.

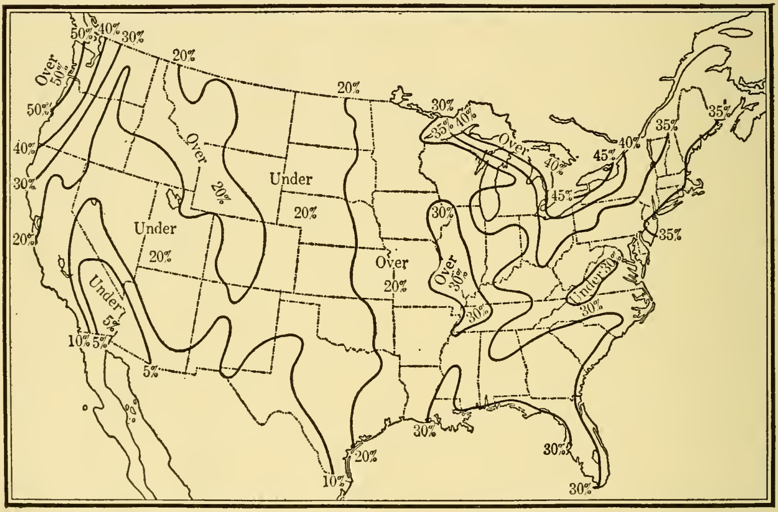

FIG. 76. Mean Annual Probability of Rainy Days

Late spring and early summer bring the greatest probability over most of the Great Plains and eastward to the Mississippi Valley. The southern Atlantic and the Gulf coast, as well as the southwestern interior, have their greatest probability in middle or late summer and early autumn. About half the United States has the greatest probability of rain in the warmer months. Summer (which is the "dry season") brings the minimum rain probability on the Pacific coast and over most of the Plateau region. East of the Rocky Mountains autumn is the dominant season of minimum probability.[1]

[1] See also W. Köppen, "Regenwahrscheinlichkeit und Bewölkung in den Vereinigten Staaten von Nordamerika," *Met. Zeitschr.*, Vol. 10 (1893), pp. 161–168.

Consecutive Days with and without Precipitation. The maximum number of consecutive days that have been recorded as passing with and without rain or snow is a matter of considerable general interest. These data do not, of course, indicate that such rainy or rainless periods occur annually, but they represent the maximum duration of these conditions within the years covered by the observations.[1] Over most of the country the number of consecutive rainy days has been between 10 and 20, these conditions characterizing by far the larger part of the districts east of the Rocky Mountains except the southern Great Plains (Texas). On the northwestern coast (western Oregon), where the rainfall is heavy and the cyclonic activity is marked, more than 30 days in succession (30–40) have been rainy, while over a considerable area centering around the Great Lakes the number has been from 20 to 30. The frequency of cyclonic rainfall in this latter section, and not the annual rainfall, clearly controls the conditions. The districts of heavier annual precipitation north of the Gulf of Mexico have had fewer consecutive days with precipitation than the Lakes. Adjoining the district of the maximum number, on the northwestern coast, a considerable area, including part of northern California, eastern Oregon, most of Washington and Idaho, has had from 20 to 30. The smallest number of consecutive days with rain or snow (less than 10) has occurred in southern California, over much of the Southern Plateau Province, and over most of central and western Texas.

From two weeks to a month (15–30 days) have elapsed without precipitation over most of the Eastern Province and from one month to two months (30–60 days) over most of the Plains, the Northern Plateau Province, and the North Pacific Province. The duration of rainless periods increases rapidly from all sides toward the arid districts of the southwestern interior, where over five months (150 days) have passed without rain or snow. Clearly, then, the duration of rainless periods is least where the rainfall is heavier, the dis-

[1] M. W. Harrington, "Rainfall and Snow of the United States," *U. S. Weather Bur. Bull. C*, 1894. Atlas, Sheet XXII, Charts 9, 10; text pages 28–29 (these charts were based on about twenty years of observations and are the latest available).

tribution through the year is more uniform, and the cyclonic activity is greater.

Over the middle Atlantic and south Atlantic states and the lower Missouri valley there has occurred on the average about once in the warm season (1895–1914) a period of 20 or more consecutive days without 0.25 in. of rainfall in twenty-four hours. Taking the same rainfall amounts and season, but a period of 30 or more consecutive days without 0.25 in. in twenty-four hours, it appears that the fewest such dry periods are found in the middle Atlantic and south Atlantic states, the upper Ohio valley, and the northern parts of New York and New England, where they occur on an average about once in three seasons. The longest period of consecutive days without 0.25 in. of rainfall in twenty-four hours during each warm season for twenty years has also been determined for selected stations east of the Rocky Mountains.[1]

Droughts.[2] Long periods without rain are generally classed as droughts. The term connotes a long spell of dry but not necessarily altogether rainless weather, resulting in damage to crops. A clear and comprehensive definition of a drought is, however, difficult to frame for the reason that the effects depend so largely upon other factors than the deficiency of rainfall; for example, the accompanying temperatures, the amount of wind movement, the character and condition of the soil, evaporation and cloudiness, the stage of the crop, and other varying controls enter into the problem. If a drought is arbitrarily expressed in terms of a deficiency in annual or seasonal or weekly rainfall of a certain percentage, it may appear that in two districts which have the same deficiency the effects are different because the other controlling factors are not the same. Droughts of greater or less intensity may occur anywhere in the United States, but are more likely to be serious where the annual rainfall is small and where cyclonic controls of precipitation are weak. They may affect large areas, or they

[1] Precipitation and Humidity section, *Atlas of American Agriculture*, Figs. 66, 67, and 69; text pages 42–43.

[2] See Precipitation and Humidity section, *Atlas of American Agriculture*, Figs. 7, 11, 15, 58–67, and 69; also text pages 42–43.

may be very local. The whole of the United States is never afflicted with a drought at one time. Weather map conditions during droughts generally show that the immediate meteorological controls are weakened cyclonic activity or somewhat unusual cyclonic paths, or both. Special studies have been made of various severe droughts in the United States.[1] An economic aspect of droughts to which special attention has recently been directed is that of their relation to the occurrence of forest fires. "A prerequisite of a forest fire is a drought."[2]

Hourly Frequency of Rainfall: Day and Night Rainfall. A study of the distribution, intensity, and frequency of rainfall brings out many interesting economic and human relations. Much of the great agricultural area east of the Rocky Mountains receives over half its warm-season (April–September) rains at night; that is, at the time when they interfere least with harvesting the staple wheat and corn crops.[3] If most of the rain fell by day there would be a greater loss of water by evaporation, the moisture would penetrate less deeply into the ground, and harvesting and threshing would be carried on at a

[1] See, for example, A. W. Greely, "American Weather," pp. 246–250; A. J. Henry, "Climatology of the United States," *U. S. Weather Bur. Bull. Q* (1906), pp. 51–56; "Rainfall of the United States," ibid., *Bull. D* (1897), p. 18. A map of the eastern United States showing the frequency of dry spells in the months of April to September during twenty years was published in the *National Weather and Crop Bulletin* for May 4, 1915. The greatest frequency was in the Plains Province, the least in the southern Appalachians. A relation between critical drought periods in the West and sun-spot cycles has been discussed by F. E. Clements ("Drouth Periods and Climatic Cycles," *Ecology*, Vol. 2 (1921), pp. 181–188).

[2] E. A. Beals, "Forecasts of Weather Favorable to an Increase of Forest Fires," *Proc. 2d Pan-Amer. Sci. Congr., Washington, U. S. A., December 27, 1915, to January 8, 1916*, Sect. II: Astronomy, Meteorology, and Seismology, Vol. II, pp. 257–270; J. A. Larsen and C. C. Delavan, "Climate and Forest Fires in Montana and Northern Idaho, 1909 to 1919," *M. W. R.*, Vol. 50 (1922), pp. 55–68; A. J. Henry, "Dry Months in the United States," ibid., pp. 484–485; E. F. McCarthy, "Forest Fire Weather in the Southern Appalachians," ibid., Vol. 51 (1923), pp. 182–185; also several papers, ibid., pp. 561–571.

[3] Precipitation and Humidity section, *Atlas of American Agriculture*, Figs. 9, 16, 17; text pages 41–42. Also J. B. Kincer, "Daytime and Nighttime Precipitation and their Economic Significance," *M. W. R.*, Vol. 44 (1916), pp. 628–633; W. J. Humphreys, "On the Differences between Summer Daytime and Nighttime Precipitation in the United States," ibid., Vol. 49 (1921), pp. 350–351 (explanation of the inequalities between day and night precipitation).

disadvantage. The maximum day rainfall during the warm season occurs over the southeastern states. It appears that while the night rains are heavy in the corn belt, the rains of daytime are the heaviest in the cotton belt. West of the Rocky Mountains about half the summer rain falls by day and half by night.[1]

Very complete studies of the details of local rainfall have been made in the case of Baltimore and of Chicago.[2] Investigations along similar lines have also been made for other localities.[3]

Heavy Rainfalls in Short Periods.[4] Mean or average rainfalls seldom occur. An excess or a deficiency is much more probable than the normal. Hence there is need of knowing something

[1] Except in Arizona.

[2] O. L. Fassig, "The Climate and Weather of Baltimore," *Maryland Weather Service*, Vol. II (Baltimore, Maryland, 1907), pp. 159–237; H. J. Cox and J. H. Armington, "The Weather and Climate of Chicago" (1914), pp. 151–236. An earlier volume, still of importance in rainfall studies in the United States, is C. A. Schott's "Tables and Results of the Precipitation, in Rain and Snow, in the United States; and at Some Stations in Adjacent Parts of North America, and in Central and South America," *Smithson. Contr. to Knowl.*, Vol. 18, *No. 222*, 1872; 2d ed., ibid., Vol. 24, *No. 353*, 1881.

[3] See, for example, the following: A. W. Greely, "American Weather" (1888), pp. 155–156; "Tables of Average Hourly Precipitation at Washington, D. C. (1874–1891), and at New York (1870–1891)," *M. W. R.*, Vol. 20 (1892), p. 79, also *Met. Zeitschr.*, Vol. 9 (1892), p. 480; F. L. Wachenheim, "Die Hydrometeore des gemässigten Nordamerika," *Met. Zeitschr.*, Vol. 22 (1905), pp. 193–211; W. P. Stewart, "Midsummer Showers at Galveston, Texas," *M. W. R.*, Vol. 41 (1913), pp. 1225–1226; E. D. Coberly, "The Hourly Frequency of Precipitation at New Orleans, Louisiana," ibid., Vol. 42 (1914), pp. 537–538; J. von Hann, "Lehrbuch der Meteorologie" (3d ed.), 1915, p. 345; H. H. Martin, "Hourly Frequency of Precipitation in Central Ohio, and its Relation to Agricultural Pursuits," *M. W. R.*, Vol. 46 (1918), pp. 375–376; G. W. Mindling, "Hourly Duration of Precipitation at Philadelphia," ibid., pp. 517–520; R. Nunn, "Hourly Precipitation at Nashville, Tennessee," ibid., Vol. 50 (1922), pp. 180–184; J. S. Cole, "The Daily Quantities in which Summer Precipitation is Received," ibid., pp. 572–575; I. R. Tannehill, "Frequency Distributions of Daily and Hourly Amounts of Rainfall at Galveston, Texas," ibid., Vol. 51 (1923), pp. 11–14; M. R. Sanford, "Hourly Precipitation at Syracuse, New York," ibid., pp. 395–396; H. G. Carter, "Variations in Hourly Rainfall at Lincoln, Nebraska," *M. W. R.*, Vol. 52 (1924), pp. 208–211; idem, "Hourly Precipitation at Topeka, Kansas," ibid., pp. 211–212; W. F. Feldwisch, "The Probabilities of 0.10 inch or more of Rainfall at Springfield, Illinois," ibid., pp. 581–583; G. M. French, "Hourly Rainfall at Los Angeles, California," ibid., p. 583.

[4] See also footnote 1 on page 230.

about the maximum amount of precipitation that has occurred, and is therefore likely to occur again or may even be exceeded. The maximum amount of water that dams, sewers, and supply pipes may at some time or other have to take care of is of vital concern to engineers. Farmers, too, are interested in this matter, because of the washing and flooding character of very heavy rainfalls.

Excessive precipitation may result either from short and heavy or from lighter but longer-continued rainfalls.[1] Rains of the former type do the most damage. These occur characteristically over the western mountain and plateau districts, and are therefore seldom recorded. The torrential downpour (cloud-burst) on the distant, uninhabited mountain slope; the sudden rise of a stream in its narrow cañon; the rush of the flood downward with irresistible force—these are familiar phenomena to many who have sought their livelihood in that rugged country. In the eastern United States excessive rains of this general type occur chiefly in summer. They are associated with thunderstorms or with West Indian hurricanes and are found chiefly along the southern Atlantic and Gulf coasts. Rains of lighter intensity and of longer duration, of the second type mentioned above, occur in connection with general storms of unusual development and are therefore found in the sections most frequently crossed by such storms, in the eastern and northeastern portion of the country, and on the northern Pacific coast. As pointed out by Greely, the conditions which give rise to such excessive rainfalls are not likely to last long. These heavy downpours are therefore usually over within a day or so.[2]

Where the line between damaging and favorable rainfalls shall be drawn depends upon a large number of factors, such as topography, soil, condition of crop, etc. Complete data concerning excessive rainfalls for year, month, day, and shorter periods are regularly published in the Annual Reports of the Chief of the Weather Bureau and in the *Monthly Weather*

[1] A. J. Henry, "Rainfall of the United States," *Bull. D*, pp. 52–54.

[2] A. W. Greely, "American Weather," p. 148.

Review. Numerous other tables of heavy precipitation, and several discussions of these data, have been published in recent years.[1]

The data regarding heavy rainfalls during the twenty-year period 1895–1914 have been charted. The heaviest recorded rainfalls in twenty-four hours varied from over 10 in. along the Gulf coast in Texas and Louisiana, where these downpours occurred in connection with West Indian hurricanes, to 4 in. over the Plains and the northeastern states (Fig. 77). On the north Pacific coast the twenty-four-hour amounts have not exceeded 5 in., although the mean annual rainfall is heaviest there. The average number of days with over 1 in. of precipitation in an hour (1895–1914) ranges from less than one day in the West and over the northern Lakes area to six days along the Gulf coast. The maximum hourly rainfall has varied between less than 1 in. over most of the country west of the Rocky Mountains to about 4 in. over the central Gulf coast states. Rains of the cloud-burst type, bringing very much larger amounts, occasionally occur in the southwestern interior (Fig. 78).

In a general description of climate the actual "record" rainfalls are of no special concern. The maximum changes as the length of the period of observation lengthens. Records are thus constantly being broken. The absolute maximum hitherto noted is, therefore, a rather accidental matter at best, and it is

[1] See, for example, C. A. Schott, loc. cit., footnote 2, page 228; A. W. Greely, loc. cit., pp. 144–150 (details of excessive rainfalls up to date of publication); M. W. Harrington, loc. cit., text pages 27–28, 59–80; Atlas, Sheet XXII, Map 8 (discussion of heaviest rainfalls, including heaviest rainfalls at selected representative stations for year, month, seventy-two, forty-eight, and twenty-four hours, with tables); A. J. Henry, loc. cit., pp. 52–58; *Summaries of Climatological Data by Sections, Bull. W.* A recent discussion and tabulation of data, mostly for the period 1896–1914, will be found in A. F. Meyer's "Elements of Hydrology" (New York, 1917), pp. 64–187 (includes data for typical excessive rainstorms; illustrated by numerous curves and charts). The most recent charts are found in the section on Precipitation and Humidity of the *Atlas of American Agriculture,* Figs. 70, 74, and 75, text page 42. Fig. 70 is here reproduced as Fig. 77, and Fig. 75 as Fig. 78. See also "Storm Rainfall of the Eastern United States," by the Engineering Staff of the Miami Conservancy, *Technical Reports,* Part V (Dayton, Ohio, 1917), 309 pages, 114 figs. (reviewed in *M. W. R.,* Vol. 47 (1919), p. 297); J. W. Alvord, "Relation between Frequency and Intensity of Precipitation," ibid., Vol. 49 (1921), pp. 441–452 (diagrams showing, for selected stations of the Weather Bureau, the relation between intensity and frequency of rainfall in storms of various durations).

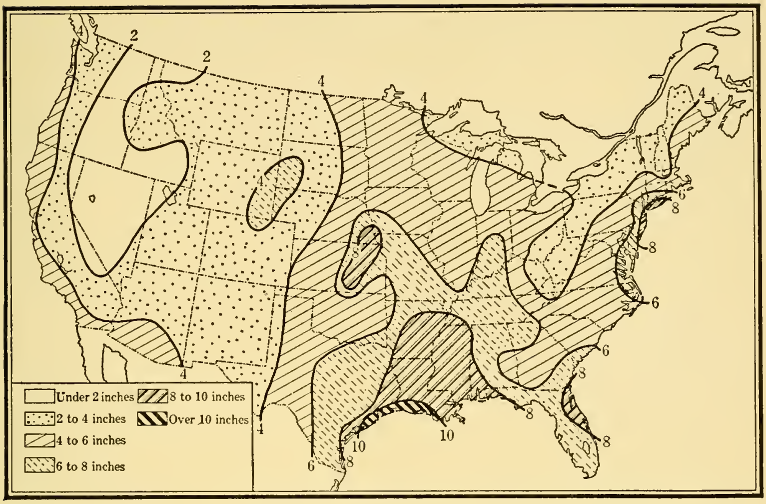

FIG. 77. Maximum Precipitation in Twenty-four Consecutive Hours, in Inches

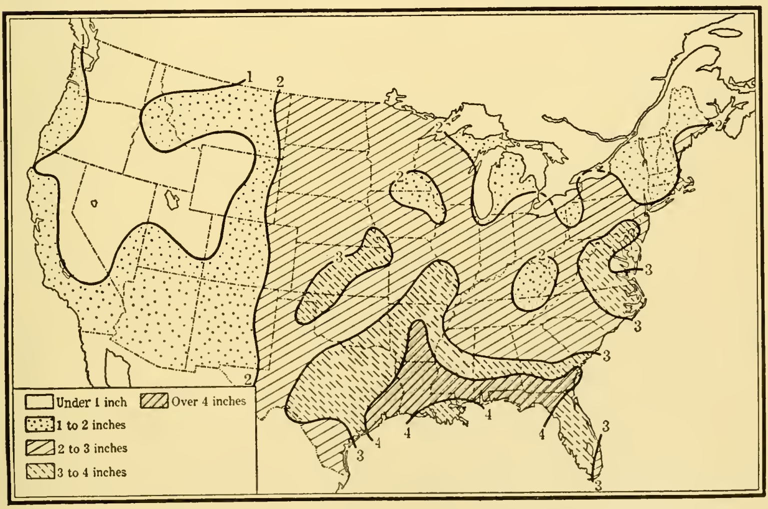

FIG. 78. Maximum Precipitation in One Hour, in Inches

hardly worth while in a general account to remember single records which are at any moment likely to change. For the present purpose broad generalizations, easily remembered, are sufficient.

As a convenient rough-and-ready classification the following rainfalls may be termed excessive: 10 in., or more, in a month; 2.50 in., or more, in twenty-four consecutive hours; 1 in., or more, in an hour. It must, however, be noted that these amounts are often reached and exceeded, and are in no way to be regarded as unusual in many sections of the country. They are especially likely to occur along the southern Atlantic and Gulf coasts in the warmer months and on the Pacific coast in winter. An examination of the available data regarding the heaviest rainfalls in the United States leads to the following simple general statement, which covers the ground fairly satisfactorily and will need no essential modification as the length of the period of observation increases. An average of 1 in. a day, for 30 days, giving 30 in. in a month, is not often exceeded, although there are a good many cases of still heavier monthly rainfalls, and one case of over 70 in. (Helen Mine, California, January, 1909). A fall averaging 1 in. an hour, for twenty-four hours, covers the heaviest daily rainfalls thus far recorded.[1] It is impossible to give any rate of rainfall covering, in a similar simple way, the amount of precipitation in spasmodic, torrential downpours which may be over in half an hour or in even less time. In a record cloud-burst (Campo, California, August 12, 1891) 11.50 in. fell in eighty minutes. This was at the rate of a little over 8.50 in. an hour, continued for an hour and twenty minutes. In some of these cloud-bursts the rate has actually been as high as 16–18 in. an hour, but continued for very short periods.

Secular Variations in Rainfall: Instrumental Records. Popular belief in a "change" of climate goes back to the early decades of the settlement of the United States, and frequent mention of the subject occurs in the literature. In the '70's and early

[1] J. P. McAuliffe, "Excessive Rainfall and Flood at Taylor, Texas," *M. W. R.*, Vol. 49 (1921), pp. 496–497 (a rainfall of 23.11 in. fell on September 9–10, 1921, the twenty-four-hour record for the United States up to that time).

'80's a widespread interest developed in the question because of the impression, which rapidly gained ground, that the building of railroads, the construction of telegraph lines, and the plowing of the soil over the western Plains were gradually bringing about a progressive increase in the rainfall over those sections of the country. Popular interest in the matter naturally led to a critical examination of the then available rainfall records, and several studies were at that time made along this line.[1] No definite evidence of any progressive secular variation in rainfall was found, in these or in other early investigations of a similar sort.[2] More recently J. Warren Smith has shown that cultivation does not increase rainfall in the semi-arid region.[3] There are well-defined sequences of increasing and decreasing annual rainfall amounts, but there has been no progressive increase or decrease during the past fifty years.

It is upon the evidence furnished by accurate instrumental records, and not upon tradition or human memory or uncertain evidence of other kinds, that reliable conclusions in this matter must be based. Accurate instruments properly exposed and carefully read do not lie, do not forget, are not prejudiced. The period covered by rain-gauge records in the United States is a comparatively short one. Few observations go back of 1850, and most of them date from later than 1870. It is not surprising, therefore, that there have thus far been comparatively few noteworthy studies of these records in relation to climatic changes.

[1] See, for example, C. A. Schott, loc. cit.; H. A. Hazen, "Variation of Rainfall West of the Mississippi River," *U. S. Signal Service Notes*, No. VII (1883), p. 8; also "Droughts in Kansas and Texas and Secular Variation in Rainfall," *M. W. R.*, Vol. 15 (April, 1887), p. 119; M. W. Harrington, loc. cit., text pages 19–20; Atlas, Sheet XXII, Map 4; J. D. Whitney, "Brief Discussion of the Question whether Changes of Climate can be brought about by the Agency of Man, and on Secular Climatic Changes in General, with Special Reference to the Arid Region of the United States," in "The United States," Suppl. I (Boston, 1894), Appendix B, pp. 290–317.

[2] See, for example, "Supposed Recent Changes in Climate" (by W. Upton and others), *Amer. Met. Journ.*, Vol. 7 (June, 1890), pp. 79–81 (the records at New Bedford, Massachusetts, from 1813, and at Providence, Rhode Island, from 1831, show no progressive change in rainfall, but there are indications of a periodicity of about twenty years).

[3] J. W. Smith, "Cultivation does not increase the Rainfall," *M. W. R.*, Vol. 47 (1919), pp. 858–860.

In the temperate zones most of the rain and snow comes, directly or indirectly, in association with general cyclonic storms. As the paths, numbers, and intensities of these storms vary more or less from year to year, it is inevitable that the precipitation of any year or of any month may differ considerably from the general average for that period. Even a single heavy thundershower or a well-developed general rainstorm may, for example, raise the total rainfall for a month 2 or 3 in. above the normal. Such annual and monthly fluctuations of rainfall are well known. As a result a single year or month, or a series of years or months, may be wetter or drier than the average. The questions whether there is any tendency toward a progressively decreasing or increasing rainfall anywhere in the United States, and whether there is any evidence of a periodic variation or oscillation in rainfall, have in recent years been discussed by Henry, Kincer, Brückner, Marvin, and others.

Henry plotted the "progressive averages of precipitation" for certain stations in southeastern New England, in the upper Ohio valley (both for the years 1834–1896), and in the middle Mississippi valley (1858–1896).[1] A rough periodicity of about nine years appears in the Ohio valley curve. The curve for the middle Mississippi valley shows little indication of periodicity. The New England curve shows a noticeable increase in rainfall, apparently a local phenomenon, from about 1845 on, with a climax in 1888–1889 (a drought period in 1880–1882 being excepted). It is apparent that the three curves are not in agreement as regards their periods of maximum and minimum. A later study of the departures from the normal of the annual rainfalls for all districts of the United States in the period 1887–1911 (twenty-five years) "lends no color to the theory of a cycle in precipitation."[2] During the twenty-five-year period under discussion the tendency seems to have been toward years of deficient precipitation, although years of abundant rainfall were interspersed. Curves for selected sta-

[1] A. J. Henry, *Bull. D*, pp. 18–24, Plate II.

[2] A. J. Henry, "Secular Variation of Precipitation in the United States," *Bull. Amer. Geogr. Soc.*, Vol. 46 (March, 1914), pp. 192–201.

tions in New England, the interior, the western Gulf, and North Carolina (1879–1911) show no "approach to uniformity of distribution in time or space." For the period and the districts under discussion, there were about equal numbers of dry and of wet years. Conditions favorable for unusually heavy rains over extended areas are apparently exceptional. Rainfalls close to or slightly below normal are rather to be expected. The annual rainfalls for a group of six long-record stations have more recently been plotted by Kincer.[1] While there are certain more or less recognizable long-period variations in the mean annual rainfall, these fluctuations seem to be local, and definite conclusions for large areas cannot safely be drawn. There is no evidence in the available data to justify the belief that rainfall is either permanently increasing or decreasing anywhere in the United States.

Brückner has shown that over the world as a whole warmer and drier periods alternate with periods which are cooler and moister in an oscillatory cycle of about thirty-five years from maximum to maximum.[2] In the case of the United States, curves are given for stations in the upper Ohio valley, the central portion of the Mississippi valley, and for New England. The rainfall for each year is taken as the average of the ten years of which it is the center; for example, for the year 1835 the average of the years 1830–1840 is taken. In all parts of the world which are represented in the curves, except New England,[3] there was a maximum of rainfall about 1845–1850; a minimum about 1860–1870; another maximum in the early

[1] New Bedford (Massachusetts), one hundred and one years; Marietta (Ohio), ninety-three years; Oregon (Missouri), Manhattan (Kansas), Boise (Idaho), and Sacramento (California), fifty years each (Precipitation and Humidity section of *Atlas of American Agriculture*, Fig. 6, text page 5).

[2] E. Brückner, "Klimaschwankungen seit 1700, nebst Beobachtungen über die Klimaschwankungen der Diluvialzeit," Vienna (1890), 324 pp.; "Zur Frage der 35-jährigen Klimaschwankungen," *Pet. Mitt.*, Vol. 48 (1902), pp. 173–178; "Klimaschwankungen und Völkerwanderungen im XIX. Jahrhundert," *Internat. Wochenschr. f. Wissenschaft, Kunst und Technik* (March 5, 1910), Berlin, 15 pp.; "The Settlement of the United States as controlled by Climate and Climatic Oscillations," *Memorial Volume of the Transcontinental Excursion of 1912 of the Amer. Geog. Soc. of New York* (New York, 1915), pp. 125–139.

[3] In the case of New England, maxima came in 1869 and 1889, the conditions being different from those inland because of marine control.

'80's, followed by a decrease until the end of the last century. From the minimum of 1836 to the minimum of 1871 there were thirty-five years, and between the maximum of 1848 and that of 1882 there were thirty-four years. There followed a cool and moist period. These oscillations have been traced back over seven hundred years in Europe, and in Brückner's opinion there is no doubt that they will continue. The size and value of crops, movements of population, and other economic consequences have been shown to depend upon these cycles. Thus, the maximum of rainfall about 1880 was followed by the "boom" on the High Plains, and the collapse of the same "boom" occurred when the succeeding dry period came on. Obviously, oscillations of rainfall will have their most far-reaching effects in regions over which the normal precipitation is barely enough for ordinary needs. Here a fluctuation on one side or the other of the mean is of critical importance. Brückner has shown that in the most continental climates the difference between the maximum and the minimum rainfalls may amount to 25 per cent or even 50 per cent, or more. The oscillations in the level of Great Salt Lake show no permanent change. The waters of the lake rise and fall with a periodicity which agrees in general with the Brückner thirty-five-year cycle. After the close of the dry period following the middle of the last century, the lake rose more than twelve feet up to about 1880, its maximum coming during a wet period. Then it fell again during the next dry period and rose during the following wet cycle.

Marvin has recently studied rainfall records in New England which go back nearly two hundred years.[1] Beginning about 1750 there was a more or less continuous and progressive diminution of rainfall in the vicinity of Boston for nearly one hundred years, until in the middle of the last century it averaged several inches a year less than it did nearly three generations

[1] C. F. Marvin, "Concerning Normals, Secular Trends, and Climatic Changes," *M. W. R.*, Vol. 51 (1923), pp. 383–390. See also A. McAdie, "Dry and Wet Seasons," *Annals Astron. Obs. Harv. Coll.*, Vol. 86, Part IV (1924), pp. 227–232. ("The method of accumulated sums must be accepted with reservation, and . . . its value as furnishing an aid in forecasting is limited. . . . A year appears to be too long a period for the detection of true seasonal departures.")

before. Then came a change, a progressive increase in New England rainfall being noted, culminating apparently in 1903, since which date there has been an irregular decrease. Marvin concludes that while there is no evidence of any permanent change in climate, more or less definite periods of from fifty to one hundred years or more seem to occur from time to time during which "the climatic conditions of a more or less limited region suffer a material change in the value of the running average of conditions. . . . Shorter periods also are found and admit of more careful analysis because of their greater number and frequency."

Secular Variations in Rainfall: Non-instrumental Evidence. Climatologists who take a broad view of their subject are interested in any facts which may throw light on the question of secular variations in rainfall. They agree, however, in the conviction that non-instrumental evidence is to be regarded as in a wholly different category from that of actual rain-gauge records, in that the former cannot possibly be subjected to the same rigid analysis and scrutiny as is the case with the latter. Non-instrumental evidence of various kinds is, however, so strong that it is agreed among the experts that there have been several glacial periods during the earth's history. The final glacial period seems to have comprised four or possibly five epochs. The last of these, reaching its climax tens of thousands of years ago, was followed by a series of similar but less marked climatic fluctuations representing the gradual dying out of the glacial impulse. Much interest naturally centers around the question whether these oscillations came to an end several thousand years ago or whether, with diminishing intensity, they continued into historic times. Or, to state the question somewhat differently, did historic times witness fluctuations in climate intermediate between those of the post-glacial stages and the much less pronounced and shorter cycles like that of Brückner referred to above?

Within the last few years Douglass has made an extensive study of the rings of trees in Arizona and in California, it being assumed that the thickness of the annual layers of tree growth gives an approximate measure of the annual amount of pre-

cipitation. Measurements of the rings of yellow pines on the northern Arizona plateau indicate a correlation between the tree growth and certain meteorological cycles.[1] By means of an empirical formula a test was made covering a period of over forty years for which actual rainfall records are available, and it was found that the rings gave a measure of the rainfall with an average accuracy of 70 to 85 per cent.[2] Indications of periods of 11.4, 21, and 33.8 years, as well as of still longer fluctuations, were found. The last crest of the 33-34-year period, about 1900, can be correlated with the Brückner period referred to above. A 100-year cycle appears very prominently in the 3000 years of the *Sequoia* record, and also in the 500 years of the yellow pine. The evidence of the sun-spot cycle varies somewhat according to the topography of the region in which the trees are located, the yellow pines in the dry regions of Arizona showing the cycle best. The climatic chronology based on tree rings has also been studied in the case of the tree trunks and beams discovered in the ruins of prehistoric dwellings in the Southwest. In addition, Douglass has found historical confirmation of the sun-spot cycles (as indicated by the tree rings in Arizona and in California) in connection with the studies of Spoerer and Maunder upon early sun-spot observations.

The results obtained by Douglass have been included by Huntington in a very considerable investigation of the various

[1] A. E. Douglass, "Weather Cycles in the Growth of Big Trees," *M. W. R.*, Vol. 37 (1909), pp. 225–237; "A Method of Estimating Rainfall by the Growth of Trees," *Bull. Amer. Geogr. Soc.*, Vol. 46 (May, 1914), pp. 321–335; "Pine Trees as Recorders of Variations in Rainfall" (*Astron. and Astrophys. Soc. Amer.; Bull. Internat. Inst. Agri.*), abstract in *Quart. Journ. Roy. Met. Soc.*, Vol. 39 (1913), pp. 244–245; "Climatic Cycles and Tree Growth," *Carnegie Publ. 289* (1919); "Evidences of Climatic Effects in the Annual Rings of Trees," *Ecology*, Vol. 1 (1920), pp. 24 *et seq.*; "Some Aspects of the Use of the Annual Rings of Trees in Climatic Study," *Scientific Monthly*, Vol. 15 (1922), pp. 5–22; "Some Topographic and Climatic Characters in the Annual Rings of the Yellow Pines and Sequoias of the Southwest," *Proc. Am. Phil. Soc.*, Vol. 61 (1922), pp. 117–122; "Conclusions from Tree-Ring Data; General Methods in the Advance of Cycle Studies" (in Report of a Conference on Cycles), *Geogr. Rev.* (*Supplement*), Vol. 13 (1923), pp. 659–661, 674–676. F. E. Clements and A. E. Douglass, "Climatic Cycles," *Yearbook Carnegie Institution*, Washington, D. C. (1918), p. 295 (discusses coincidence of drought in the Southwest with years of maximum sun spots, and mentions further tree-ring examinations to be made with this in mind). See also footnote 1 on page 239.

[2] In the case of the older trees certain corrections were applied.

kinds of evidence of climatic "changes" during the past three thousand years in the arid Southwest. This investigation involved a study of the rings of the Big Trees of California and of prehistoric ruins, archæological remains, strand lines, dunes, and alluvial terraces in southern Arizona and New Mexico.[1] A comparison of the curves showing the rapidity of growth of the Big Trees with curves previously plotted, illustrating changes of climate in central and western Asia, leads Huntington to the conclusion that there is a correspondence between them as far back as 1200 B.C., the agreement being especially pronounced during the period A.D. 400–1600. When allowance is made for revision of the Asiatic curve according to the discoveries of Stein,[2] Butler,[3] and others, and for the revision of the tree curve by Antevs,[4] the resemblance between the two curves becomes quite close from about 1000 B.C. to the present time. Moreover, the growth of the trees since rainfall records have been kept shows a high degree of correlation with the rainfall in Palestine. Therefore Huntington concludes that the growth of the Big Trees furnishes an approximate indication of fluctuations in climate not only in California but in the similar climate of western Asia. Under other climatic conditions the fluctuations may be of different types. The archæological and physiographic evidence in the United States seems to Huntington to run closely parallel to similar evidence in the

[1] E. Huntington, "The Fluctuating Climate of North America," *Geogr. Journ.*, Vol. 40 (September–October, 1912), pp. 264–280, 392–411 (abridged and reprinted in *Smithson. Inst. Ann. Report for 1912*, Washington, D. C. (1913), pp. 257–268); "The Shifting of Climatic Zones as illustrated in Mexico," *Bull. Amer. Geogr. Soc.*, Vol. 45 (1913), pp. 1–12, 107–116; "Secret of the Big Trees, Yosemite, Sequoia, and General Grant National Parks," *Publ. U. S. Dept. of the Interior* (1913), 24 pp., 14 figs.; "The Secret of the Big Trees," *Harper's Magazine*, Vol. 125 (1912), pp. 292–302. See, especially, "The Climatic Factor as illustrated in Arid America," by Ellsworth Huntington, with contributions by Charles Schuchert, Andrew E. Douglass, and Charles J. Kullmer, *Carnegie Inst. of Washington, Publ. 192* (1915), iii and 341 pp. Also "Climatic Changes" (New Haven, 1922), xiii and 329 pp., and "Tree Growth and Climatic Interpretations," *Carnegie Inst. of Washington, Publ. 352* (1925).

[2] M. A. Stein, "Serindia," 1921; "Ruins of Desert Cathay," 1912.

[3] H. C. Butler, "Desert Syria, the Land of a Lost Civilization," *Geogr. Rev.*, Vol. 9 (1920), pp. 77–108.

[4] Ernst Antevs, "The Big Tree as a Climatic Measure," *Carnegie Inst. of Washington, Publ. 352* (1925), 153 pages.

Old World. In the United States the archæological evidence is interpreted by Huntington and others as indicating at least three periods during which a much larger population was living in the Southwest than seems to be possible at present, owing to the existing deficiency of water supply. The curve of the Big Trees suggests to these investigators that these epochs of denser population may have occurred during three long wet periods between and after three major dry periods which seem to have culminated about 1200 B.C. and in the seventh and thirteenth centuries of the Christian Era.

The Conservative Attitude regarding Non-instrumental Evidence of Climatic Changes. Climatologists as a group do not feel competent to weigh such facts as those adduced by Huntington and others regarding climatic oscillations long before the days of instrumental records. They realize that the proper understanding and critical analysis of botanical, archæological, and physiographic evidence require a degree of technical knowledge which is usually not a part of their own scientific equipment. Therefore it must be left to the experts to weigh this evidence and to determine its value. In connection with this it may be stated that these experts are not unanimous in their views. It has been pointed out that the growth of tree rings may be affected by many conditions other than the annual rainfall. The distribution of precipitation through the year may locally exercise a more critical control than the annual amount, although the age of the tree, the normal cycles in the tree's growth, insect and other pests (often themselves coming periodically), overcrowding, loss of shelter, topography and other factors, are also concerned. It should, however, be noted that the importance of these controls varies according to the locality and the climate, and that allowance may often be made for these variables. It may further be noted that where large numbers of trees from different localities are averaged together, as has been done by Douglass, Huntington, and Antevs, these minor irregularities disappear. While there is a general agreement that curves based upon the examination of the rings in hundreds of trees do indicate climatic fluctuations, there is considerable diversity of opinion as to the relative importance

of temperature, rainfall, and the length of the growing season in determining the character of these changes.[1]

Further, there is some opposition among geologists to the view that variations in erosion and in lake levels, due to variations in rainfall, furnish the proper explanation of the conditions which have been observed in the dunes and alluvial terraces. In a region of active mountain growth, like the Southwest, elevation of the land may explain some of the facts whose interpretation has been sought in climatic change. Lastly, the archæological evidence is by no means regarded as conclusive by all the experts. Thus, J. W. Fewkes and others believe that long-continued prehistoric irrigation, leading to increasing salinity of the soil, was perhaps more potent in causing human migrations than human enemies or increasing aridity.[2] Migration in search of firewood, and invasions of enemy tribes, as well as a reduction in the fertility of the soil, may help to explain these prehistoric changes of population.

In the face of such conflicting testimony on the part of the experts, the conservative climatologist may well remain open-minded on the more technical aspects of this whole question.[3] The real nature and intensity of the historic fluctuations in climate and their effects on man are subjects which still need much critical study.[4]

[1] See E. Antevs, "Die Jahresringe der Holzgewächse und die Bedeutung derselben als klimatischer Indikator," *Progressus Rei Botanicae* (Jena, 1917), Vol. V, pp. 285–386.

[2] J. W. Fewkes, *28th Ann. Rept. Bur. Amer. Ethn., 1906–1907* (1912). There is abundant literature on the archæology of the Southwest. See, for example, the following publications: E. L. Hewett, J. Henderson, and W. W. Robbins, "The Physiography of the Rio Grande Valley, New Mexico, in Relation to Pueblo Culture," *Smithsonian Inst., Bur. Amer. Ethn. Bull. 54* (1913), 76 pp. (pp. 41–70 on climate and the evidence of climatic changes. A progressive desiccation of the region since the beginning of the pueblo and cliff-dwelling period is thought to be indicated, but the change in population may possibly be ascribed to other causes); H. S. Colton, "The Geography of Certain Ruins near the San Francisco Mountains, Arizona," *Bull. Geogr. Soc. Phila.*, Vol. 16 (April, 1918), pp. 1–24 (discusses the ruins as affording evidence of climatic oscillations).

[3] C. E. P. Brooks, in "The Evolution of Climate" (London, 1922), p. 149, says that the evidence of the trees "appears to have decided the battle in favor of the supporters of change."

[4] For a discussion of the climate in late glacial and post-glacial times, see Ernst Antevs, "On the Pleistocene History of the Great Basin," *Carnegie Inst. of Washington, Publ. 352* (1925), pp. 51–114.

CHAPTER XI

SNOWFALL

THE ECONOMICS OF SNOW · THE MEASUREMENT OF SNOWFALL · GENERAL CONTROLS OF SNOWFALL; SNOWSTORMS; TWENTY-FOUR-HOUR SNOWFALLS · THE MEAN ANNUAL SNOWFALL MAP OF THE UNITED STATES · SNOWFALL OF THE PACIFIC SLOPE · SNOWFALL OVER THE PLATEAU PROVINCE · SNOWFALL ON THE GREAT PLAINS · SNOWFALL OF THE EASTERN UNITED STATES · NUMBERS OF DAYS WITH SNOWFALL AND WITH SNOW COVER; AVERAGE DATES OF SNOWFALL · SLEET AND ICE STORMS (GLAZE) · IS SNOWFALL DECREASING?

The Economics of Snow. The margin of temperature-difference between rain and snow is a narrow one. It is, however, one of the most critical points in man's relation to the atmosphere because of the fundamental differences in the economic effects of rain and snow. Snow, especially the deep snow which lies for weeks and months on the mountains and plateaus of the semi-arid West, furnishes a slower and therefore a more lasting natural supply of water for power, for irrigation, and for general use than does rain, which has a quick run-off. In the drier sections of the United States many of the most important problems with which engineers have to deal—whether in connection with railroad construction and operation, or hydraulics, or irrigation, or general water supply—are connected with the depth and conditions of snowfall and with the amount of water which its melting will supply. In California the mountain snowfall has well been termed the "lifeblood" of the state, and the same is true of most of the vast territory west of the Rocky Mountains. The farmers throughout the districts of deficient precipitation are deeply concerned with the amount of winter snowfall, for the melting snows supply most of the water needed for irrigating the crops. A winter snow cover prevents

deep freezing of the ground, protects grasses and fall-sown crops, and provides spring moisture for growing vegetation.

When sufficiently deep, and more or less permanent, snow makes sleighing possible, and greatly facilitates lumbering operations over the forested sections of the northern and northeastern states. Heavy winter snows, on the other hand, interfere with railroad operation, sometimes causing serious and expensive interruption of transportation and involving great expense for the removal of snow from steam and electric railroads and from city streets. At the same time such conditions furnish employment to thousands of men. An open winter, with light snowfall, means a saving of millions of dollars to the railroads and cities in the snow belt. In the latitudes of heavy snowfall, snow-sheds, snow-fences, and snow-plows are essential to a reasonably uninterrupted railroad service. The demand for all kinds of rubber footwear in the states where snowfall is a common winter characteristic has given rise to one of the important manufacturing industries of the snow belt. The use of snowshoes and of skis for winter sports as well as for ordinary means of locomotion is another result of a winter snow cover.

In the construction of buildings account must be taken of the maximum possible weight of snow which the roof may have to support. Building regulations in certain northeastern cities allow for forty pounds per square foot on a flat roof. A steeply sloping roof will obviously have less load to carry. In the districts of very heavy snowfalls in the Sierra Nevada and Cascade mountains the weight of snow is much greater. When unusually heavy snowfalls occur in localities where the amounts are generally relatively small, and where the roofs are not strong enough to support the excess load, serious disasters may result, as was the case when the roof of the Knickerbocker Theater, in Washington, D. C., collapsed during a performance at the end of January, 1922.

The Measurement of Snowfall. The accurate measurement of snowfall presents many difficulties, and no reasonably simple, practical, and satisfactory method for general use has yet been

devised.[1] Most of the available records are still of rather doubtful accuracy. What is needed is careful determination both of the depth of snow as it falls and also of the water equivalent of the snow when melted. The widely quoted average ratio of ten inches of snow to one inch of water is subject to very wide fluctuations, for it depends upon the varying density and quality of the snow. The essential difficulty in obtaining accurate measurements by means of any ordinary form of gauge results from the effect of the wind in preventing the snow from falling into the gauge. In calms or during light winds there is little or no error, but when there is much wind such a gauge, unless properly protected or screened in order to break the force of the wind, will give too small a catch, the deficiency becoming greater as the wind velocity increases.

In view of the economic importance of the amount of water available for irrigation and power in the Western states, considerable study has been made, especially during recent years, of the whole problem of the more exact determination of the depth of snowfall and of its water equivalent. Various improvements in snow gauges which weigh the snow directly have been made by Marvin, Fergusson, Rotch, and Fitzgerald, but there still remains the difficulty of securing an accurate catch. Marvin has devised a large shielded weighing gauge which has given fairly satisfactory results at some stations, but there have been difficulties with it on account of the blocking of the top of the collector during wet and sticky snows and by frozen snow, as well as by reason of its being crushed by the weight of very deep snow.[2] In snows which accumulate to a depth of many feet a very large gauge becomes necessary, and there are many difficulties which are not met with where snows are light. In the regions of very heavy snowfalls on the higher uninhabited elevations of the Western states there is the difficulty of visiting the gauges during the winter and of constructing a gauge of some sort which may catch, and record, the snowfall of a whole season. Snow

[1] See also R. E. Horton, "The Measurement of Rainfall and Snow," *Journ. New Eng. Water-Works Assoc.*, Vol. 33 (1919), pp. 14–71; abstract in *M. W. R.*, Vol. 47 (1919), pp. 294–296.

[2] Described in Circular E, Instrument Division, U. S. Weather Bur.

"bins" of various forms, standpipes, platforms, and other devices have been tried, without much success. The best seasonal gauge for snows of whatever depth seems to be the Mougin *Totalisateur*, employed in the high Alps in connection with the study of the growth of glaciers.[1] This gauge consists of an elevated reservoir containing a salt solution in which the falling snow is immediately melted irrespective of temperatures. By the simple expedient of determining the decreased salinity whenever the gauge is visited, the amount of precipitation into the reservoir for the preceding period can be accurately calculated. Although the effect of the wind was somewhat overcome by placing a Nipher screen around the orifice, no feasible method was found to prevent clogging due to frost feathers or sticky snow.

Various methods have also been used for measuring the depth of snow by means of snow stakes, and of melting cross sections of snow in order to determine the average density of the snow cover. J. E. Church, Jr., of the University of Nevada, has obtained good results by cutting out and measuring tubular sections of the deep snows of the Sierra Nevada by means of the Mount Rose "snow sampler," especially designed for this work.[2] In this instrument vertical snow cylinders are cut out by means of several sections of tubing of small diameter, and the water content of this sample is determined by weight, the dial of the spring balance being graduated to indicate the depth of water instead of its weight. The chief feature of the snow sampler is a shouldered cutter fitted with teeth to cut rebellious crusts and raise the cores without material loss. B. C. Kadel has also designed a snow sampler which has lately been improved as a result of practical experience in its use.[3]

[1] Les Variations Périodiques des Glaciers des Alpes Suisses. Rapports 35–36 (1914–1915), pp. 238–241, par Dr. Paul-Louis Mercanton.

[2] J. E. Church, Jr., "Snow Surveying: its Problems and their Present Phases with Reference to Mount Rose, Nevada, and Vicinity," *Proc. 2d Pan-Amer. Sci. Congr.*, Sect. II, Vol. II (Washington, D. C., 1917), pp. 496–547 (a general discussion of the problem, with references to the literature); "Snow Surveying for the Forecasting of Stream Flow," *Engin. News-Record*, Vol. 86 (1921), pp. 244–248, 300–304. See also H. F. Alps, "Foot-Layer Densities of Snow," *M. W. R.*, Vol. 50 (1922), pp. 474–475, and J. M. Sherier, "Mountain Snowfall and Flood Crests in the Colorado," ibid., Vol. 51 (1923), pp. 639–641.

[3] B. C. Kadel, "An Improved Form of Snow Sampler," *M. W. R.*, Vol. 47 (1919), p. 697.

This instrument consists of three parts: a tube for holding the sample while it is being weighed, a cutter for bounding the area of the sample, and a spring balance. It differs essentially from the Mount Rose snow sampler in having a larger orifice.

To ascertain in advance the amount of water which will each year be available from melting snow, surveys are now made of western mountain slopes, particularly along the crest and at outposts on either side. The courses upon which the seasonal percentage of this intervening snow cover is based occur at intervals of several miles, and a survey unit or quadrangle may include several streams. So uniform, usually, are the seasonal percentages obtained on the various courses, even over long distances, that the amount of run-off even for adjacent basins can be closely estimated. Surveys are made monthly from January to April to determine the increase in the snow cover, and from May to July to determine its melting and the probable run-off still due. Surveys of this kind, which originated at the Mount Rose Observatory, will undoubtedly be greatly extended by the Weather Bureau in the near future. A *Seasonal Snow Survey and Forecast of Stream Flow,* conducted jointly by the state of Nevada and the Nevada section of the Weather Bureau, is published by J. E. Church, Jr., in charge of the Nevada Coöperative Snow Surveys.

In the matter of forecasting the amount of water available from snow, the rate of melting of the snow, as well as the amount of evaporation from the snowfields and from the surfaces of water-storage basins, is obviously of great consequence. Some years ago J. N. Le Conte devised a method for determining the mean rate of melting of the snows in the Sierra Nevada Mountains of California.[1] This matter has been further discussed by McAdie, who has designed a model by means of which the actual curve of melting for a given season may be compared with the mean curve, and thus the probable date of the disappearance of the snow may be determined.[2]

[1] J. N. Le Conte, "Snowfall in the Sierra Nevada," *Bull. Sierra Club,* Vol. 6 (1908), pp. 310–314.

[2] A. G. McAdie, "The Principles of Aërography" (1917), pp. 226–229. Fuller discussions by the same author may be found in *M. W. R.*, Vol. 38 (1910), pp. 940–941; Vol. 39 (1911), pp. 445–447; Vol. 41 (1913), pp. 1092–1093.

Henry has investigated the weather conditions which may modify or control the disappearance of the snows in the high Sierras of California.[1] The most pronounced "snow flood" in the United States is that which passes annually down the Columbia River and which is due almost wholly to the melting snows on the mountains of the Columbia drainage basin. Otherwise "snow floods" are generally rare in the United States, flood conditions being usually brought about by a combination of snow-melting and of heavy rainfall. In the high Sierras the most favorable weather conditions for the conservation of the snow cover are low temperatures and little wind movement. When these conditions prevail the average loss by evaporation is about three quarters of an inch per month. Relatively high temperature, active wind movement, and abundance of strong sunshine are the most unfavorable conditions for the conservation of a snow cover. Under these conditions the loss of freshly fallen snow may average ten inches a day, and of old snow three to four inches.[2] In connection with the disappearance of snow, the influence of forests upon the rate of melting and evaporation deserves more extended study than it has yet received. While a forest checks air movement and thus tends to decrease evaporation, the trees, by holding snow on their branches or, in the case of conifers, on their needles, naturally increase the surface from which evaporation may take place. In the case of the yellow-pine forest near Flagstaff, Arizona, the spring rate of melting in the forest is noticeably slower than that over the adjacent grass and farmland park area.[3]

[1] A. J. Henry, "The Disappearance of Snow in the High Sierra Nevada of California," *M. W. R.*, Vol. 44 (1916), pp. 150–153.

[2] See, however, J. E. Church, Jr., "Snow Density in Relation to Run-off," *Eng. News-Record*, Vol. 92 (1924), p. 234 (abstract). As reported by F. S. Baker, about 14 per cent of the total snowfall evaporated during the winter of 1915–1916 at the Utah Forest Experiment Station, this being about equivalent to 3 inches of water ("Some Field Experiments on Evaporation from Snow Surfaces," *M. W. R.*, Vol. 45 (1917), pp. 363–366).

[3] A. J. Jaenicke and M. H. Foerster, "The Influence of a Western Yellow Pine Forest on the Accumulation and Melting of Snow," *M. W. R.*, Vol. 43 (1915), pp. 115–124; also J. E. Church, Jr., "The Conservation of Snow: Its Dependence upon Forests and Mountains," *Sci. Amer. Suppl.*, Vol. 74 (1912), pp. 152–155, and *Met. Zeitschr.*, Vol. 30 (1913), pp. 1–10.

The observations of snowfall at the regular stations of the Weather Bureau are made by means of ordinary gauges, the amount of melted snow being included in the general record of "rainfall." In addition, the number of inches and tenths of inches of snowfall for each twenty-four-hour interval is determined as accurately as possible by measurements made at places where the snow is of average depth. These observations have been used as the basis of the snowfall maps of the United States hitherto published.

General Controls of Snowfall; Snowstorms; Twenty-four-Hour Snowfalls. The major controls of snowfall in the United States are the temperature, the season of precipitation, the frequency and intensity of winter storms, the topography, the proximity to primary sources of moisture supply such as the oceans and the Great Lakes, and the exposure to damp winds. The heaviest snowfall is to be expected where the winter season naturally has abundant precipitation and where the temperatures are low enough to give snow instead of rain. Such conditions are found on certain mountains, as on the Sierra Nevada for example, where the low temperatures are due to the altitude; or on damp lowlands, as in the vicinity of the Lakes, where the climate is continental and the winters are therefore cold. The temperature control over snowfall is clearly indicated in the decrease in the amount of snow toward the south and also along the Atlantic coast, where, during the winter months, rain frequently falls with onshore winds while it is snowing in the interior, not many miles away.

Over the eastern United States as a whole the northeast wind, being both cold and damp, is the chief snow-bringer. A "northeast snowstorm" is a familiar winter characteristic, especially along the Atlantic coast.[1] Most of the heaviest snows usually come in midwinter or in late winter, or even in March over the northern sections. The northwest winds, blowing on the rear of the storms, are cold enough to give snow,

[1] C. F. Brooks, "The Snowfall of the Eastern United States," *M. W. R.*, Vol. 43 (1915), pp. 2–11; idem, "New England Snowfall," ibid., Vol. 45 (1917), pp. 271–285. See also "The Winter Snowfall of 1922–1923 in the Eastern United States," *Bull. Amer. Met. Soc.*, Vol. 4 (1923), p. 60.

but are generally too dry. Snow-flurries rather than deep and general snows are therefore usually associated with them. Exceptions must, however, be made in the case of windward mountain slopes, as in the Appalachian area, and of places to leeward of the Great Lakes, where the northwest winds may bring heavy snowfalls. The first snow of the season, which in northern sections usually comes in the autumn, is generally associated with squally, cold, damp northwest winds on the rear of a retreating cyclonic storm. New England, the middle Atlantic states (especially their northern portion), the Great Lakes region, and the Ohio and upper Mississippi valleys have the most frequent heavy snows, especially the two first-named districts.[1] In an intensive study of two great snowstorms Brooks has brought out certain characteristics of snowfall distribution which are doubtless of common occurrence.[2] Snow fell over a wide area on each side of the storm track. The heaviest snows came with northeast winds over a belt about one hundred to two hundred miles in width to the north of the track. The northwest winds, in the southwest quadrants of the storms, sprinkled light snows over the country as far as about three hundred miles to the southward of the track. A distinct "patchiness" in the distribution of these snowfalls resulted from local topographic features. Many snowstorms have been recorded which are memorable because of their very heavy snowfalls. These become the outstanding snowstorms of tradition, of history, or of meteorological record. The famous "March blizzard" of 1888 will long be spoken of in southern New England and eastern New York.[3]

It is a general characteristic of heavy snowfalls in eastern districts, especially on mountains, that they are accompanied

[1] See "Weather Forecasting in the United States," *U. S. Weather Bur. No. 583* (1916), pp. 253–256 (Figs. 163–166 illustrate snow-type weather maps for southern New England, the northern Rocky Mountain region, and the northern interior).

[2] C. F. Brooks, "The Distribution of Snowfall in Cyclones of the Eastern United States," *M. W. R.*, Vol. 42 (1914), pp. 318–330, 11 charts.

[3] See Chapter XVI. Notable snowstorms are usually discussed in the *Monthly Weather Review*. See, for example, P. C. Day and S. P. Fergusson, "The Great Snowstorm of January 27–29, 1922, over the Atlantic Coast States," ibid., Vol. 50 (1922), pp. 21–24 (refers to other memorable storms).

by fairly high winds. A marked contrast to this condition is found in the region of very deep snows on the Sierra Nevada Mountains of California, for example, where the winds are relatively light.

The greatest twenty-four-hour snowfalls in the different sections of the country have been summarized by Henry as follows: northeast, 2–3 feet; elsewhere east of the Mississippi River, from 8 in. (Ohio valley) to 18–20 in. (along the lower Lakes); southern states, 4–8 in.; Mississippi Valley, 5 in. (Vicksburg) to 20 in. (St. Louis); northern Plains, 9–17 in.; Rocky Mountains, 8–24 in.; Plateau and northern Pacific coast, 10–20 in.[1]

The Mean Annual Snowfall Map of the United States. The standard snowfall map of the United States at the present time was constructed by Kincer and is based on the records of about twelve hundred stations for the twenty-year period 1895–1914.[2] While it was possible to draw lines of equal depth of snowfall for five-inch differences over the eastern portion of the country, it was necessary to use wider intervals in the western mountain areas, where snowfall conditions vary greatly.

Snow falls with more or less regularity each winter everywhere in the United States except in southern Florida, the lowlands of southernmost California adjacent to the ocean,

[1] A. J. Henry, "Climatology of the United States," *Bull. Q*, pp. 58–59.

[2] Fig. 79, below, is redrawn from Fig. 76 in the section on Precipitation and Humidity of *Atlas of American Agriculture*. In *M. W. R.*, Vol. 47 (1919), p. 695 and Chart XVII, the map originally prepared by Kincer was published in a somewhat different form, having been revised slightly by C. F. Brooks "to bring it into conformity with certain obvious topographic influences, and the detailed maps of the United States east of the Mississippi, 1895–1913, and of New England, 1895–1916, without, however, getting away from the basic averages for the twenty-year period." (See loc. cit. in footnote 1, page 248.) Current data regarding snowfall may be found in the *Annual Reports of the Chief of the Weather Bureau*; in the *Monthly Weather Review* (including the *Annual Summary*), and in the monthly and annual reports of *Climatological Data* which are issued for the section centers. Averages, covering periods of years, may be found in the *Summaries of Climatological Data by Sections*, and in A. J. Henry's "Climatology of the United States," *Bull. Q*. Both the last-named publications also contain in their texts brief statements concerning snowfall. Maps showing the depth of snowfall for each month appear regularly during the winter in the *Monthly Weather Review*. The first snowfall map of the United States was constructed by Harrington on the basis of data covering the general period 1884 to 1891. A reproduction may be found in F. Waldo's "Elementary Meteorology" (1896), Fig. 108, p. 344. A later chart, by

and southwestern Arizona. Most of this snow falls from December to March, but at the higher elevations and in the northern states it begins earlier and also falls later. There is considerable variation in the latitudes which mark the southernmost limits of snowfall in any given winter, but for purposes of convenience and of easy memorizing the limiting latitudes of regular and of occasional snowfall may be broadly generalized as follows:

Latitudes of Regular and of Occasional Snowfall

District	Regular	Occasional
Pacific coast	45° (northern Oregon)	34° (Los Angeles)
Interior	30° (northern Gulf)	26° (southeast Texas)
Atlantic coast	35° (Hatteras)	29° (northern Gulf)

From a practical point of view it may be said that snow does not occur in sufficient amount to lie unmelted on the ground south of San Francisco on the lowlands of the Pacific coast, or south of Cape Hatteras on the Atlantic coast. This statement, however, does not hold for inland districts or for elevated areas. The southern boundary of a regular winter snow cover in ordinary winters may be put at about latitudes 40°–42° in the eastern United States, but occasional winters carry the

A. J. Henry, for the general period 1884 to 1895 (the data covering varying numbers of years from three to eleven), was published in *M. W. R.*, Vol. 26 (March, 1898), Chart XI, text page 108. A note is appended to the chart, stating that the snowfall of the Sierra Nevada and Rocky mountains is "much greater" than is shown on the chart. Monthly charts showing the average depth of snowfall from October to May inclusive, based on records of varying lengths from five to twenty years, mostly not over seven years (1884–1891), were published in 1891 by Harrington (*U. S. Weather Bur. Bull. C* (1894), Plate XVIII, text pages 16–17). See also C. F. Brooks, "The Snowfall of the United States," *Quart. Journ. Roy. Met. Soc.*, Vol. 39 (1913), pp. 81–84, Plate II. (This mean annual snowfall map is based on observations made at about two thousand stations during the fifteen winters from 1895 to 1910. In the case of the earlier maps the observations which were used came mostly from near sea level, and for that reason the heavy snowfalls on the mountains and at the higher elevations generally were not indicated. In Brooks's map use was made of observations obtained at the higher altitudes as well as the lower. Topographic effects were also taken into account, and the map therefore showed for the first time the actual conditions of snowfall over the whole country with as close an approach to accuracy as was possible with the then available data.)

snow cover a good deal farther south. It is one of the marked climatic characteristics of the eastern United States that snow not infrequently occurs unusually far south, in districts which have very mild winters. The lines on the accompanying map show the average annual depth of snowfall in inches on the general basis of twenty years of observation (Fig. 79). Therefore, they do not indicate the maximum or minimum depths which have been recorded in this period, or the depths in any single year. It must furthermore be remembered that the amount of snowfall varies greatly and very irregularly from year to year. Years of abundant snows, well exceeding the average depth, alternate irregularly with years of deficient snowfall. This variability depends on the length and severity of the winter and on the paths, number, and intensity of the snowstorms.

Snowfall of the Pacific Slope. One of the most striking facts on the snowfall map is the effect of the topography in causing very heavy snowfalls on the western flanks of the Sierra Nevada and Cascade ranges, reaching from 400 to 500 in. in some places. No line of equal depth of snowfall is drawn on the map for over 100 in., greater amounts being shown by figures.[1] Thus a depth of 527 in., the maximum anywhere on the map, is indicated over the central Sierra Nevada. The next greatest depths are 459 in. over the northern Cascades in Washington and 430 in. over the Cascades of Oregon. The snowfall over the lowlands of the Pacific slope is of little importance. It is very light, even in the north, and seldom excites interest except when occasionally, at long intervals, snow falls in southern districts where it is so uncommon as to be a curiosity, or when a heavier fall than usual in the northern districts causes comment. Snow is practically unknown on the immediate coast south of the northern boundary of California (latitude 42° N.), but it is frequent on the mountains, even in southern California. When snow does occur on the lower lands of southern California, it seems always to fall with hail, sleet, or rain.

[1] In Brooks's map of 1913 (see footnote on page 251) lines showing depths of 100, 200, 300, and 400 in. are drawn over portions of the Sierra Nevada and Cascade ranges.

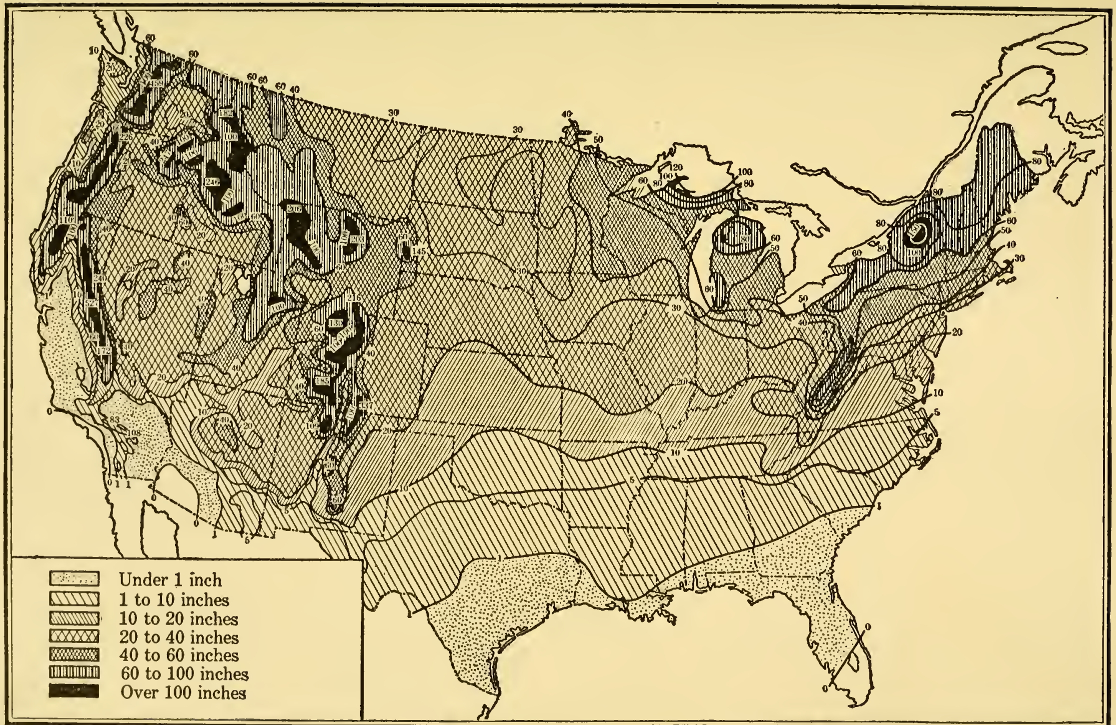

FIG. 79. Average Annual Snowfall in Inches, Unmelted

Interest is, however, naturally very great in what has for years enjoyed the distinction of being the area of heaviest snowfall in the United States. This area, on the western slopes of the high Sierras of California, has been closely studied along the line of the Southern Pacific Railroad which connects Sacramento, California, and Reno, Nevada. Recent discussions by McAdie[1] and Palmer[2] have brought out many interesting facts regarding this remarkable snowfall. The average seasonal snowfall at Summit, Placer County, California (7017 ft.), is somewhat over 400 in.; at Tamarack, Alpine County, California (8000 ft.), it is somewhat over 450 in. During the season of 1879–1880, 783 in. of snow fell at Summit, and in 1888–1889, 776 in. At Tamarack, in 1906–1907, 884 in. were recorded, and in 1910–1911, 770 in.

These totals by no means represent a very heavy annual precipitation (rain and melted snow combined). The significant fact is the proportion of the whole which falls as snow. The increase in annual precipitation with increase of altitude, which is a general characteristic of mountains, is rapid up to a certain height, above which the rate lessens, and finally there is a decrease in precipitation with altitude. A maximum amount of rainfall, including melted snow, is reached at between six thousand and seven thousand feet.

Railroad operation in this region shows many responses to the heavy snowfall, as all travelers over the Southern Pacific route through Summit well know. The famous "thirty miles of snow-sheds" cost $42,000 a mile over single track and $65,000 over double track. About $150,000 is spent annually for upkeep and renewals. The life of a shed averages a little over twenty years. Fire-fighting trains are kept always in readiness in case of fire. These sheds are planned to sustain snow sixteen feet deep. If the depth is greater, shoveling by hand must be resorted to. Even then the weight of the snow is occasionally so great that sections of the sheds collapse. In some cases concrete has been used instead of wood. The upkeep and

[1] See footnote 2 on page 246.

[2] A. H. Palmer, "The Region of Greatest Snowfall in the United States," *M. W. R.*, Vol. 43 (1915), pp. 217–221 (with illustrations).

replacement of these sheds is so expensive that the plan of eliminating them altogether and substituting powerful locomotives and rotary snow-plows has been under investigation. A heavy rain-and-snow gauge has been completely crushed by the snow, and a fence made of two-inch boiler flues has been bent. The gables of the houses are all built at sharp angles, so that the snow may slide off.[1]

Some recent observations on Mt. Rainier, Washington, indicate that the snowfall in that district is extraordinarily heavy.[2] Daily records of snowfall were kept during most of the season of 1916–1917 at Paradise Inn, on the south slope of Mt. Rainier, at an elevation of 5500 feet. Observations were not begun until November 24, 1916, when there were 36 in. of snow on the ground. From that date until the last snowstorm before midsummer, 1917, the total depth of snowfall was 789.5 in. The record at Paradise Inn is the first obtained west of the summit of the Cascades in Washington at so great an elevation. The railroads cross the mountains at comparatively low levels. The season of 1916–1917 does not appear to have been one of unusually heavy snowfall, nor is Paradise Inn located at what would theoretically seem to be the region most favorable for a maximum precipitation. It is not unlikely, therefore, that still deeper snows will eventually be recorded at greater altitudes than 5500 feet on Rainier, which would then attain the distinction of having the greatest snowfall in the United States.

Snowfall over the Plateau Province. The "snow-shadow" effect of the western mountain barrier causes a decrease in the depths of snowfall over the interior Plateau district as a whole, with larger amounts over the mountains and higher plateaus. Most of the winter precipitation here comes in the form of snow. The essential feature of the snowfall distribution is the general decrease over the valleys and less elevated portions

[1] A. H. Palmer, "Snow and Railway Transportation," *M. W. R.*, Vol. 47 (1919), pp. 698–699 (with illustrations).

[2] L. C. Fisher, "Snowfall on Mt. Rainier," *M. W. R.*, Vol. 46 (1918), pp. 327–330. Since 1918–1919 the seasonal depths of snowfall at Paradise Inn have been as follows: 1919–1920, 489.9 in. (record began September 11, the depth then on the ground being included in the mean); 1920–1921, 676.0 in.; 1921–1922, 718.0 in.; 1922–1923, 565.0 in.

from about 20 to 30 in. or more in the north to less than 1 in., and even to 0, in the extreme south. Over these districts of light snowfall the ground usually does not remain covered many days at a time, and in the region of the lower Colorado River, in southwestern Arizona and southeastern California, snow is rarely seen except on the mountains. The mountains and more elevated plateaus have decidedly heavier snows.

As is to be expected, the Rocky Mountains, because of their continental location, have less snow than the Pacific coast ranges. Nevertheless, from 200 to 300 in. or more are indicated for some of their western slopes. A depth of 337 in. is shown in the mountains on the Colorado-New Mexico border, of 298 in. in north-central Colorado, and of 246 and 247 in. in Idaho and northeastern Oregon respectively. In Wyoming, and even as far south as northern New Mexico, about 200 in. fall in an average year.[1]

The snowfall in the Colorado mountains is much greater than the summer rainfall and comes largely in the spring months. Most of the rivers of the Plateau states have their sources in the higher mountains, and the slow melting of the snows, which usually last well into the summer, supplies these streams with water which is essential for irrigation. The maximum stream-flow ordinarily comes in late spring or early summer, when the melting of the mountain snows is most rapid. It is a saying among the Indians of Arizona that when the last snow disappears from the mountain tops the late-summer rains are about to begin.

Snowfall on the Great Plains. East of the Continental Divide the snowfall again rapidly decreases, the lines of equal depth extending in a general east-and-west direction under the control of latitude. Lying to leeward of the Rocky Mountains, and being far from any considerable source of water vapor, the Plains inevitably have relatively little snowfall. Their total annual precipitation is less than 20 in., and most of this falls

[1] In Brooks's map (1913) lines showing amounts of over 100 in. are drawn over fairly large areas of the Rocky Mountain system even as far south as northern New Mexico, reaching over 300 in. in southern Wyoming and 400 in. in parts of the Colorado Rockies.

in summer. Thus winter is a dry season, and the snowfall which it brings is light. Even in the extreme north, in eastern Montana, where the winters are very cold and practically all the precipitation of the five or six colder months is in the form of snow, the average annual snowfall is between 30 and 40 in. The winter storms do not, as a rule, give much snow. Even the "blizzards" are not usually accompanied by heavy snows. They are dangerous to cattle and occasionally to human beings, because of the bitter cold of their northerly winds, and because these same winds carry fine ice spicules and are also filled with blowing snow which makes it difficult or impossible to see. Severe blizzards are, as a matter of fact, not so common as most people think. A whole winter sometimes passes without a typical blizzard.[1] Over the southern Plains, owing to the warmer winters, the snowfall decreases to about 20 in. in northern Kansas and to about 1 in. in central Texas. It is a characteristic of the snowfall over the northern Plains that most of it falls at temperatures well below freezing. For this reason it is light and dry and is easily carried by the strong winds, which blow it into ravines and other depressions, leaving the ranges for the most part bare and accessible for grazing. In the south the snow soon melts under the warm sun. Over the mountains which border or interrupt the Plains, it snows more frequently and during a longer season. The melting of these deeper snows furnishes much of the water which is used for irrigation along the rivers flowing to the eastward toward the Mississippi.

Snowfall of the Eastern United States. In the eastern half of the country the dominant control over snowfall is latitude, as is evidenced by the general east-and-west trend of the lines of equal depth of snow on the map. Subordinate, but nevertheless important controls are found in the effects of topography (the Appalachians, the Adirondacks, and the White Mountains of New Hampshire), of the frequency of cold, damp storm winds (Great Lakes and northeastern sections), and of the warm waters of the Gulf Stream (southern Atlantic coast). The

[1] See Chapter XVI.

depth of snow decreases to the west of the Lakes because winter is there a relatively dry season, and to the south because of the higher temperatures. The Appalachian Mountains and plateaus carry the lines well to the south, and the warm waters of the Gulf Stream carry them northward along the coast. In the vicinity of the Great Lakes, especially on their lee shores, and thence eastward along the Canadian boundary as far as New England, there is a belt of relatively heavy snowfall.

The heavier snowfall on the eastern shores of the Lakes (for example, at Grand Haven, Michigan, and at Buffalo and Oswego, New York) than on the western shores (Milwaukee, Wisconsin, and Toledo, Ohio) results chiefly from the frequent occurrence of westerly snow squalls on the lee shores after the cold winds have crossed the warmer lake waters.[1]

In parts of the upper peninsula of Michigan the average annual amounts reach 120 in.; in places in the Adirondack Mountains 150 in. or more are observed, and in northern New England the depths average over 80 in. The central Appalachian area is conspicuous because of its large snowfall (80–100 in.). Detailed studies of the snowfall of the eastern United States have been made by Brooks.[2] These show clearly the local modifications which result from the topography and from exposure to damp winds. More snow is seen to fall on the western than on the eastern slopes of the Appalachians, except in Vermont.

Over the northern tier of states, in the eastern half of the country, snow is a factor of considerable economic importance, especially over northeastern sections where the depths are greatest. Sleighing is often possible for weeks at a time in winters of abundant snowfall, the depth of snow on the ground

[1] See also C. L. Mitchell, "Snow-Flurries along the Eastern Shore of Lake Michigan," *M. W. R.*, Vol. 49 (1921), pp. 502–503.

[2] C. F. Brooks, "The Snowfall of the Eastern United States," *M. W. R.*, Vol. 43 (1915), pp. 2–11 (includes original charts showing the average depths of snowfall by months, from September to May; the average annual snowfall (1895–1913); the average annual number of days with snowfall; the mean annual, maximum and minimum annual, and extreme annual range of snowfall about the Great Lakes for the period 1895–1910; also monthly charts showing the directions of the snow-bearing winds). Also, idem, "New England Snowfall," ibid., Vol. 45 (1917), pp. 271–285 (includes charts of average monthly snowfall for November to April, also other charts of the snowfalls in special months and seasons, together with a relief map of New England).

reaching two or three feet in certain sections. Such snows greatly facilitate the lumbering industry by making it possible to use heavy sledges for hauling the logs out of the forests. Open winters, on the other hand, make lumbering difficult and expensive. Warm winter rains are especially characteristic of the Atlantic coast sections and naturally occur with increasing frequency toward the south, quickly melting any snow which happens to be lying on the ground. In the spring months heavy rains of this type, or unseasonably high temperatures unaccompanied by rains, not infrequently cause a very rapid melting of the deeper snows lying in the mountains, and produce freshets and floods in the Ohio and other river systems of the northeast.

The season of snowfall over northern sections is a long one. Snow in measurable amounts may fall as early as October, especially over the mountains and to leeward of the Great Lakes, and as late as May. The higher elevations, such as the White Mountains of New Hampshire and the Adirondacks of New York, may have snow in September and even in summer. Snowstorms of considerable intensity have occurred in April. The heaviest snowfalls usually come in February; at times early in March. The general snow cover advances as a whole from north to south with the advance of winter, very irregularly and often with many retrogressions as well, its southern margin being uneven and broken under the control of varying conditions of topography, storm control, and temperature. It usually reaches its southernmost limits in January or in February and then retreats northward again. The advance and retreat from month to month, with its many irregularities, can be studied to advantage on the charts showing the total snowfall, in inches, for each month, and the depth of snow on the ground at the end of the month, published in the *Monthly Weather Review*.

Toward the south, as latitudes of milder winters are reached, the season during which snow may fall becomes shorter and shorter. Less and less of the precipitation of the colder months falls as snow, and more and more comes in the form of snow and rain mixed, and then of rain. From the belt of heavy snowfall over the northern tier of states the depth decreases

rapidly to about 20 in. in southern Illinois, Indiana, and Ohio, and in central Virginia. To the southward of this belt the rate of decrease is somewhat less rapid, but by the time the Gulf Province is reached, the amount of snowfall is practically negligible (under 1 in.). Occasionally at long intervals there are measurable amounts in northern and even central Florida. Years may go by without snow along the Texas coast and in the lower Rio Grande valley. Much interest attaches to the occasional occurrence of unusual snowfalls in the South. During spells of exceptional cold, snow may fall to the depth of a good many inches at various localities along the southern Atlantic coast and in the Gulf states and, with diminishing depth, even as far as extreme southeastern Texas. On such occasions thousands of people witness their first snowstorm.

Numbers of Days with Snowfall and with Snow Cover; Average Dates of Snowfall. Snow affects man and his activities in so many ways that as much information as possible concerning it is naturally desired. Thus, "When does the first snow come in autumn?" "How many days with snowfall are there likely to be each winter?" "How long does the snow cover usually stay on the ground in an average year?" are questions which are naturally asked by many people of widely varying interests, and satisfactory answers to them can be given. The first autumnal snows usually fall before the middle of September locally in the Rocky Mountains, before October 1 in northernmost Michigan, and about the middle of December in the central parts of the south Atlantic and Gulf states.[1] Farther south, snow falls more and more irregularly. Along the immediate coast of the Gulf of Mexico there may even be none at all during a whole winter (Fig. 80).

The geographical distribution of the average number of snowy days[2] shows clearly the effect of latitude, of altitude, and of proximity to the ocean (Fig. 81). The chart is, however, somewhat misleading, in that snow falls more often on the

[1] Precipitation and Humidity section, *Atlas of American Agriculture*, Fig. 77, here redrawn as Fig. 80. In the West the data have reference to the lower levels only.

[2] That is, days with 0.01 inch or more of snow, melted. Fig. 81 is redrawn from Fig. 79 in the Precipitation and Humidity section.

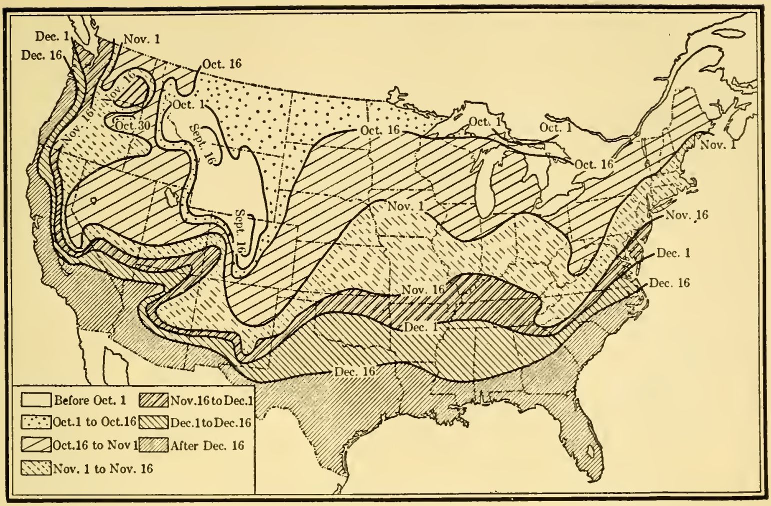

FIG. 80. Average Date of First Snowfall in Autumn

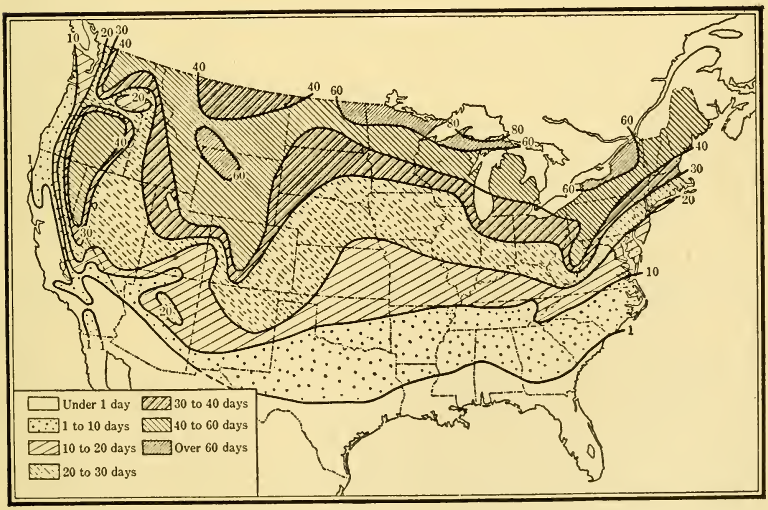

FIG. 81. Average Annual Number of Days with Snowfall

0.01 inch, or more, melted

higher western mountains than is indicated, the observations being made at the lower altitudes only. From a maximum of over sixty days with snowfall over considerable sections of the eastern United States along the Canadian border in the general vicinity of the Great Lakes,[1] the number of snowy days decreases rapidly with latitude. There is an average of only one day with snowfall along a line reaching from southeasternmost North Carolina across southeastern South Carolina, southern Georgia, Alabama, and Mississippi and thence westward across Texas and including the lowlands of central and southern California. The mountainous section of the Southern states which are crossed by the Appalachians has more days with snowfall and more snow than the surrounding lowlands and valleys, but the accumulation of snow is not sufficiently great to be a factor in causing dangerous spring floods as is the case farther north.

Finally, snow covers the ground east of the Rocky Mountains for an average annual number of days (not necessarily consecutive) exceeding one hundred and twenty, that is, four months, along the northern border (Fig. 82).[2] With decreasing latitude snow lies on the ground less and less of the time and soon becomes an almost, and then an entirely, negligible factor. When it falls over much of the South it is merely a matter of temporary discomfort, melting soon. Southern South Carolina is practically exempt from snowfall. In Georgia when snow falls it melts almost immediately, although it may remain on the ground a few days in sheltered places in northern sections of the state. It is not an uncommon occurrence for a season to pass without snow enough to cover the ground over the northern portions of the northern Gulf coast states. Farther inland (in Tennessee, for example) the ground is rarely covered more than a very few days at a time, but unusually heavy snowstorms, at long intervals, may result in a snow cover which lasts a week or even more.

Most of the central and northern portion of the Plateau

[1] Extreme upper Michigan has eighty days.

[2] Precipitation and Humidity section, Fig. 78, here redrawn as Fig. 82. West of the Rocky Mountains the data are for the lower altitudes only.

Province has from three weeks to a month or more of snow cover; the northern Pacific coast has less than ten days, and southwestern Arizona less than one day. Generalizing broadly, it may be said that the number of days with snowfall is about half the number of days with snow cover over northern sections. With decreasing latitude, in the warmer districts, the snow naturally melts more rapidly, and therefore the number

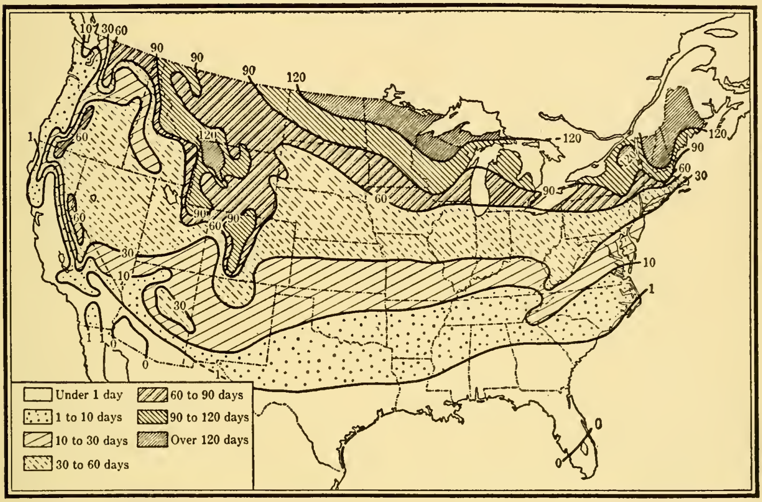

FIG. 82. Average Annual Number of Days with Snow Cover

of days on which snow falls and the number of days during which it lies on the ground are more and more nearly the same.

Sleet and Ice Storms (Glaze). Sleet and ice storms, the latter officially called *glaze*, are so closely associated with snowstorms in the eastern United States that it is often difficult to forecast snow because a storm of sleet or ice may occur instead. According to the present Weather Bureau definition, sleet is precipitation that occurs in the form of frozen or partly frozen rain. It is formed by snow that becomes appreciably melted on falling through a stratum of air which has a temperature above freezing into or through another stratum which is cold

enough to freeze some or all of the raindrops.[1] When, under these general conditions, raindrops fall to the earth's surface and freeze on coming in contact with solid objects on that surface, an ice-storm, or glaze, results. Telegraph, telephone, and trolley wires, trees, sidewalks, and streets, are then covered with an icy coating. When the accumulation of ice is heavy, and especially when there is a high wind, there is liable to be very great damage to telegraph, telephone, and open-air electrical transmission lines. Service is thus often interrupted because of broken wires, and transportation becomes difficult or dangerous by reason of slippery rails and streets. Considerable damage is often done to forest and fruit trees by such ice-storms. Verne Rhoades of the United States Forest Service has called attention to the widespread damage caused by a single ice-storm in the southern Appalachians;[2] and W. W. Ashe, Forest Inspector of the Forest Service, has pointed out that the damage done by these storms is such that the dates of past ice-storms may be determined by an examination of the trees. In the case of trees damaged by a recent ice-storm along the Blue Ridge Mountains in Amherst County, Virginia, evidence was found of injury by two previous storms, about fourteen and thirty-five years, respectively, before the last one.[3]

Frankenfield has made a study of sleet-storms and ice-storms in the United States.[4] The region of maximum frequency is over

[1] C. F. Brooks, "The Nature of Sleet and how it is formed," *M. W. R.*, Vol. 48 (1920), pp. 69–72. For special studies of severe ice-storms in recent years see C. LeR. Meisinger, "The Precipitation of Sleet and the Formation of Glaze in the Eastern United States, January 20 to 25, 1920, with Remarks on Forecasting," ibid., pp. 73–80; A. J. Henry and others, "The Great Glaze Storm of February 21–23, 1922, in the Upper Lake Region," ibid., Vol. 50 (1922), pp. 77–82 (with illustrations). An unusually severe ice-storm occurred in New England on November 27–29, 1921. In many places trolley cars stopped running, there was no telephone or telegraph service, streets became impassable, and hundreds of trees collapsed under the weight of the ice. The damage ran well up into millions of dollars.

[2] Verne Rhoades, "Ice Storms in the Southern Appalachians," *M. W. R.*, Vol. 46 (1918), pp. 373–374.

[3] Ibid.

[4] H. C. Frankenfield, "Sleet and Ice Storms in the United States," *Proc. 2d Pan-Amer. Sci. Congr.*, Washington, D. C., 1917, Sect. II: Astronomy, Meteorology, and Seismology, Vol. II, pp. 249–257 (discussion, pp. 252–257) (gives a map showing the average annual frequency of sleet-storms and ice-storms, and typical weather maps favorable for their occurrence). See also "Weather Forecasting in the United States," *U. S. Weather Bur. No. 583* (1916), pp. 256–260, Figs. 167–170.

a broad central belt reaching from west of the Mississippi eastward and northeastward to the Atlantic. This is in general the portion of the country which is crossed by the principal storm areas, with their cold northerly winds on the north, and warm southerly winds on the south of their centers. These conditions are essential to sleet formation. Severe sleet-storms may occur from November to March inclusive, and occasionally in April and October, to the north of the forty-second parallel. It appears that steep northward temperature gradients and high temperatures over the Gulf and south Atlantic states are necessary for sleet formation, and are usually absent before and during heavy snows. Surface temperatures preceding sleet-storms and ice-storms are below freezing (usually between 22° and 28°), and the high temperatures in the south which precede the sleet are accompanied by south-easterly to southerly winds.

The ice-storms of New England have been discussed in some detail by Brooks,[1] who has based his study chiefly on the very complete records obtained at Blue Hill Observatory, Massachusetts, and has included a consideration of upper-air conditions. Three general types of wind conditions produce ice-storms. These are (1) warm air arriving over residual cold air ("southerly" type); (2) cold air coming in below and warm air arriving above ("northeasterly" type); (3) cold air pushing in from the north or west below a rain-cloud ("north-westerly" type). Classifying ice-storms according to the positions and movements of the low pressure and high pressure conditions which produced them, there are seen to be two large groups. The first includes storms with anticyclones in the north dominating southern cyclones, and the second includes those in which the cyclones and anticyclones were in regular sequence.

Is Snowfall Decreasing? There is a widespread popular belief in many parts of the country, especially in the earlier settled sections of the northeast, that less snow falls now than was the

[1] C. F. Brooks, "The Ice Storms of New England," *Annals Astron. Obs. Harv. Coll.*, Vol. 73, Part I (1914), 8 pages, 2 plates (abstract in *M. W. R.*, Vol. 42 (1914), pp. 455–457); idem, "Three Ice Storms," *Science*, August 8, 1913, pp. 193–194.

case years ago. In New England, for example, it is customary to speak of the "old-fashioned New England winters" which brought many heavy snowstorms, when snow lay on the ground uninterruptedly all winter, and when sleighing was possible for three or four months without a break. It is a mistake to compare differences in snowfall on the basis of memory, which is at best short, defective, and in the highest degree untrustworthy. The tendency inevitably is to exaggerate past events, to remember a few exceptional seasons which for one reason or another made a deep impression, and very much to overrate some special event. Individual severe winters which, as they occur, are some years apart, seem, when looked back upon from a distance of several years later, to have been close together. It is much as in the case of the telegraph poles along a railroad track. When we are near the individual poles, they seem fairly far apart, but when we look down the track the poles seem to stand close together. The difference in the impressions upon youthful and adult minds may account for part of this popular belief in changes of climate. To a youthful mind a heavy snowstorm is a memorable thing. It makes a deep impression, which lasts long and which in later years, when snowstorms are just as heavy, seems to dwarf the recent storms in comparison with the older. Changes of residence may account for some of the prevailing ideas about changes of climate. One who was brought up as a child in the country, where snowdrifts are deep and where roads are not quickly broken out, and who later removes to a city, where the temperatures are slightly higher, where the houses are warmer, and where the snow is quickly removed from the streets, naturally thinks that the winters are milder or less snowy than when he was a child.

When instrumental records, scattered though they are, and difficult as it is to draw general conclusions from them, are carefully examined from the time when they were first kept in this country (which in a few cases goes back a century or more), there is found no evidence of any progressive change in the amount of snowfall. Some winters now bring deeper snows and greater cold; others are mild and "open." These varia-

tions result from differences in the numbers, intensity, and paths of winter storms, as is clearly seen by a study of the daily weather maps. This same sort of variability was characteristic of the past and will continue in the future. In other words, a mild winter with light snowfall is just as "old-fashioned" as one with severe cold and heavy snowfall. There were plenty of both kinds of winters in the past, and there will be plenty of both kinds in the future.

In his "Climatology of the United States," Lorin Blodget, in a chapter on the "Permanence of the Principal Conditions of Climate," speaking of the evidence for and against climatic change, held that "real history would be more valuable than anything else if it could be relied on, but there is great looseness with much exaggeration in everything dating back beyond the use of instruments." Blodget believed that "the Northmen found the New England coast eight hundred and sixty years ago quite precisely the same in climate as now—wild vines growing in a very few of the most favored spots, and only in these."

Dr. Hugh Williamson is quoted as saying in 1770 that the winters of the last half-century had been milder than formerly; and Professor Samuel Williams of Harvard College, whose lectures were among the foundation-stones of American meteorology, asserted that "the winter is less severe, cold weather does not come on so soon." These views sound singularly like those which are heard expressed nowadays. It so happens that the early settlers of New England made a special point of keeping a chronicle of weather conditions, so that a record of the character of the seasons running back over three centuries is available. When these old accounts are examined, it at once becomes apparent that New England had precisely the same variability in its winters in the earlier days of its settlement as now. There are accounts of great cold; of deep snows; of violent winter storms. There are also many descriptions of very mild and open winters. Thus, we read of December and January resembling May and June; of flowers growing in the woods in midwinter; of so little snowfall "as scarcely to give opportunity for enjoying the music of the sleigh bells"; of

"green Christmases"; of "winter turned into summer"; of the "ground bare for the most part"; of little ice; of crocuses up, of wild violets in bloom, and of lilacs "throwing out their leaves" in January. As the result of a rather detailed comparison of historical accounts of "old-fashioned" and of recent snowy winters in New England, covering three centuries, Brooks concludes that a "real old-fashioned snowy winter" was in the past and still is experienced on the average about once in a lifetime.[1] The winters of 1915–1916 and of 1922–1923 in New England were clearly the equals of historic snowy ones. The winters of 1917–1918 and of 1919–1920 were also cold and stormy, whereas those of 1916–1917, 1918–1919, and 1920–1921 were "open." Unusually snowy winters may predominate for a series of years or even of decades, and there are other times when "open" winters seem to be the usual occurrence. Again, C. J. Root has made a study of the snowfall data for a number of stations in the Northern states, and concludes that heavy snows will occur in the future as in the past and that present "records" will probably be exceeded.[2]

If a list were compiled of heavy snowstorms, of droughts, of floods, of severe cold, of mild winters, of heavy rains, and of other similar meteorological phenomena for one of the early settled portions of the United States, beginning with the date of the first white settlements and extending down to the present day, we should have the following situation. Dividing this list into halves, each division containing the same number of years, it would be found, speaking in general terms, that for every mild winter in the first half there would be a mild winter in the second; for every long-continued drought in the first there would be a similar drought in the second; for every "old-fashioned" winter in the first there would be an "old-fashioned" winter in the second; and so on through the list. In other words, weather and climate have not permanently or progressively changed from the time of the landing of the Pilgrims down to the present day.

[1] C. F. Brooks, "New England Snowfall," *M. W. R.*, Vol. 45 (1917), pp. 271–285.
[2] C. J. Root, "Are we having Less Snowfall?" ibid., Vol. 51 (1923), pp. 355–356.

CHAPTER XII

HUMIDITY, EVAPORATION, AND SENSIBLE TEMPERATURES

RELATIVE HUMIDITY AND ITS DISTRIBUTION · ABSOLUTE HUMIDITY AND ITS DISTRIBUTION · EVAPORATION · SENSIBLE TEMPERATURES · MEASUREMENT OF SENSIBLE TEMPERATURES · SENSIBLE TEMPERATURES IN THE UNITED STATES

Relative Humidity and its Distribution. Atmospheric humidity has many relations to life—human, animal, and vegetable. To a considerable degree it affects the sensation of heat or of cold which human beings experience. It is one of the controlling climatic influences in the growth and development of crops and of all forms of plant life. Both directly and indirectly it affects many of man's activities. Damp air is desirable in the manufacture of cotton, linen, hemp, and jute, and is a disadvantage in manufacturing hygroscopic and other articles that are injured by moisture. "Artificial climates" are being increasingly resorted to in factories in order to overcome unfavorable conditions of moisture, as well as of temperature. Relative humidity—that is, the ratio between the amount of moisture in the atmosphere and the amount which could be present, without condensation, at the same temperature and under the same pressure—is an expression of the physical moisture or dryness of climate in relation to its temperatures. Relative humidity is a real and definite factor in climate. It is directly indicated by organic substances. It reacts upon them.

The first chart with lines showing equal values of relative humidity for the United States was that of Loomis.[1] Since

[1] Elias Loomis, "Contributions to Meteorology, being Results derived from an Examination of the Observations of the United States Signal Service and from Other Sources," *Amer. Journ. Sci.*, 3d Ser., Vol. 20 (1880), pp. 1–21, Plate I. The data related to a very few stations between latitudes 30° and 45° N., east of the Rocky Mountains, for January, 1875.

then numerous later charts have been published, covering all months as well as the year, and based on increasingly complete data.[1] The present standard set of charts is to be found in the section on Precipitation and Humidity of the *Atlas of American Agriculture*.[2]

It is impossible to show the distribution of relative humidity over the United States satisfactorily and accurately by means

[1] See, for example, the following: Frank Waldo, "Elementary Meteorology," 1896 (Fig. 114 shows the average annual relative humidity in the United States, but no statement is made as to the source of the chart or the period covered by the observations). H. A. Hazen, "The Distribution of Moisture in the United States," *Annual Report of the Chief of the Weather Bureau for 1897–1898* (1898), pp. 327–338, Plates VI–VII, diagrams V–IX. (The plates illustrate "waves of moisture, pressure, and temperature" for individual dates; the diagrams show fluctuations of dewpoint, of dewpoint and temperature, and diurnal range of moisture.) F. H. Bigelow, "The Vapor Tension on the Sea Level, the 3500-foot and the 10,000-foot Planes," ibid., 1900–1901 (1902), Vol. II, pp. 420–422 (gives monthly and annual charts of relative humidity at sea level, and monthly and annual charts of normal vapor tension at sea level and on the 3500-foot and 10,000-foot planes). *Annual Report of the Chief of the Weather Bureau for 1901–1902* (1902), pp. 317–320 (three charts of normal relative humidity for January, July, and the year, based on data covering varying periods of time from four to fourteen years. Data given in tables. No author's name and no discussion). K. S. Johnson, "Mean Monthly and Mean Annual Relative Humidity Charts of the United States," *Rept. So. Afr. Assoc. Adv. Sci. for 1906* (1907), pp. 161–168 (contains mean annual and mean monthly charts of relative humidity, based chiefly on the period 1888–1901, although in some cases shorter records were taken into account but given less weight. The data were not reduced to the true daily mean. Lines are drawn for differences of 10 per cent).

For tabulations and discussion of relative humidity data see, in addition to the above, the following: W. B. Stockman, "Temperature and Relative Humidity Data," *U. S. Weather Bur. Bull. O*, 1905; A. J. Henry, "Climatology of the United States," *U. S. Weather Bur. Bull. Q* (1906), p. 61 (Table VIII, pp. 106–109, contains the monthly mean values of relative humidity for 8 A.M. and 8 P.M., 75th-meridian time, for a number of selected stations).

[2] This section was prepared, under the direction of P. C. Day, by J. B. Kincer (see pages 45–47, Figs. 85–106). For a more complete discussion see P. C. Day, "Relative Humidities and Vapor Pressures over the United States, including a Discussion of Data from Recording Hair Hygrometers," *M. W. R. Suppl. No. 6* (1917), 61 pages; charts and diagrams. With the exception of one set of maps (namely, those for 3 and 11 P.M. for January, April, July, and October) all the charts included in this monograph are to be found in the *Atlas*. Also, a somewhat different set of stations for illustrating the annual march of relative humidity and vapor pressure is used in the *Atlas* (compare Day's Figs. 1–3 with Fig. 89 in the *Atlas*). The set of *Climatic Charts of the United States*, published by the Weather Bureau, includes four charts showing lines of equal mean relative humidity for 8 A.M. and 8 P.M., 75th-meridian time, for January and July. The observations used were those made at regular Weather Bureau stations during the twenty-five-year period 1889–1913 inclusive.

of charts showing the mean monthly values, as can be done in the case of temperature and of rainfall. The most extensive series of observations available for about two hundred regular Weather Bureau stations cover the period 1888–1913 and relate to 8 A.M. and 8 P.M., 75th-meridian time.[1] But the mean of such twice-daily observations does not always give the true daily mean, and the data are not strictly comparable for all parts of the country because of the difference in local time at which the observations were made.[2]

Some of the essential facts regarding the geographical distribution of relative humidity over the United States are shown in Figs. 83–86.[3] The general system followed by the lines of equal relative humidity is simple and easily remembered. (1) On the Pacific, Atlantic, and Gulf coasts the lines

[1] Figs. 91–98 in the *Atlas* show the average relative humidity for those hours for January, April, July, and October.

[2] To the west of the Rocky Mountains the 8 A.M. readings are found to approach the maximum for the day, and the 8 P.M. approach the minimum, the average of the two being close to the twenty-four-hour mean. In the East, however, the 8 A.M. observations give values considerably higher than the daily means, and those for 8 P.M. are appreciably lower. With progress westward, owing to the earlier local time, the departures from the daily means become increasingly greater. The only extensive series of observations made at the same hour of local time (2 P.M.) covers the five-year period 1876–1880 for about ninety stations (Figs. 85–88, in the *Atlas*, show the average relative humidity at 2 P.M., local time, for January, April, July, and October). But the period is short, the observations were not as carefully made as at present, and the psychrometric tables then used were not as accurate as those now employed. Hence the data are not considered to be directly comparable with averages for longer periods and for later years. It is pointed out that the 2 P.M. average relative humidity is not very different from the average minimum for the twenty-four-hour period, the minimum, however, usually coming later than 2 P.M. and being a little lower. It is only in recent years that hygrograph records have been available for some Weather Bureau stations. With these exceptions no direct observations of the daily minimum relative humidity have been made. For this reason the average daily minimum relative humidity has been computed for April, July, and October from the average 8 P.M. (75th-meridian time) vapor pressure and the saturation pressure corresponding to the average daily maximum temperature (Figs. 99–101, *Atlas*). The values for January were not computed because of (1) the large temperature variability and (2) the frequency of temperatures below freezing. The lowest average daily minimum relative humidity is shown to be less than 15 per cent in southern Arizona, southwestern New Mexico, and extreme southwestern Texas in April. In July most of the southern Plateau has less than 20 per cent. The highest values are over 70 per cent on the extreme northwestern coast of Washington and at Cape Hatteras in July and in October, and over the eastern part of Cape Cod in October.

[3] Redrawn from Figs. 91, 93, 95, and 97 in the *Atlas*.

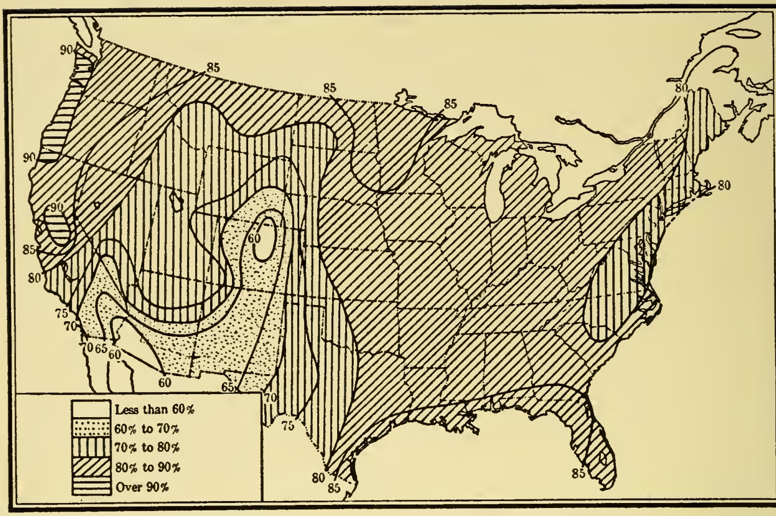

FIG. 83. January Average Relative Humidity, 8 A.M., 75th-Meridian Time

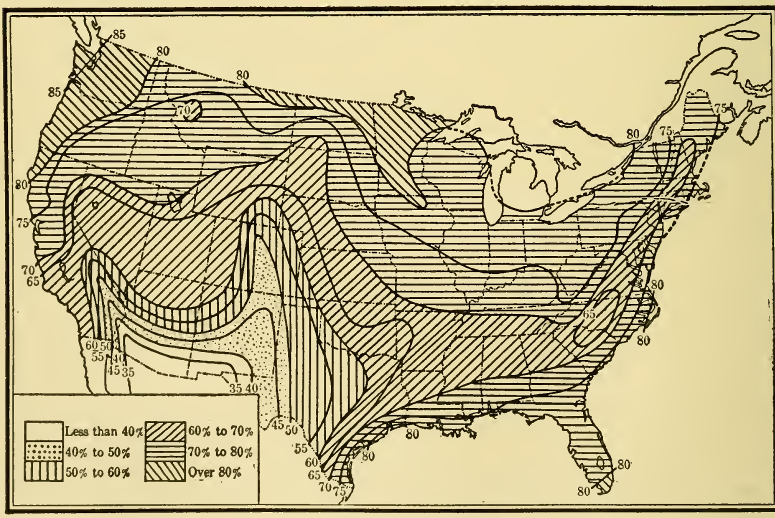

FIG. 84. January Average Relative Humidity, 8 P.M., 75th-Meridian Time

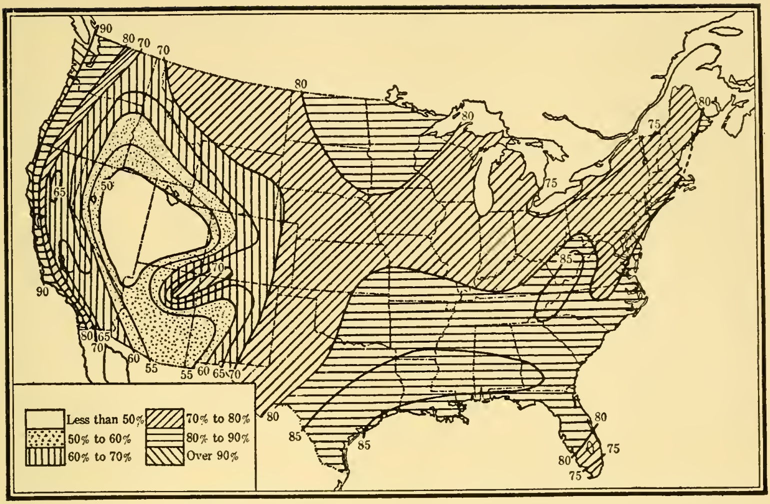

FIG. 85. July Average Relative Humidity, 8 A.M., 75th-Meridian Time

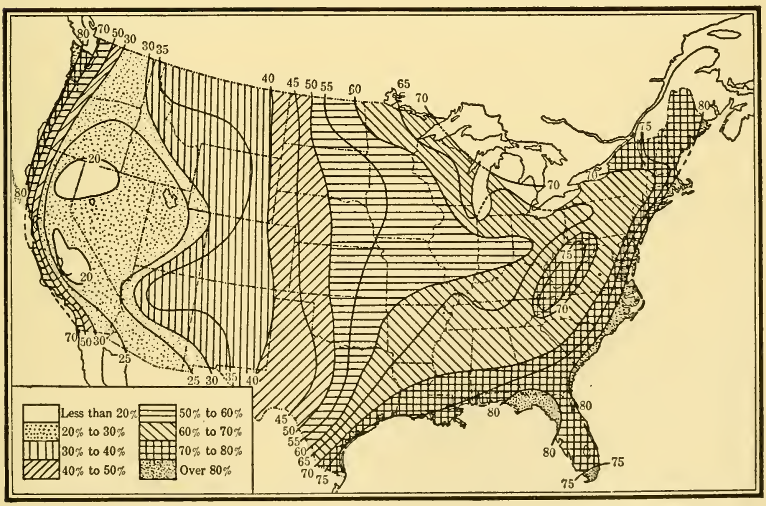

FIG. 86. July Average Relative Humidity, 8 P.M., 75th-Meridian Time

show a distinct tendency to parallel the seacoast. This feature is most clearly indicated on the Pacific slope, and there in the warmer months. (2) Over the interior Plateau the lines group themselves in a general oval pattern around central or southern centers of minimum humidity. (3) Over the Great Plains the lines of equal relative humidity lie more or less parallel with the meridians, as was discovered by Loomis in 1880, especially in the central and southern sections. The geographical distribution of relative humidity thus briefly outlined depends on a number of controls. Among these the most important are (1) the temperature, (2) the direction of the prevailing winds, (3) the distance and direction of the chief source of moisture supply, and (4) the topography. A belt of uniformly high relative humidity along the coasts averages about 75 to 80 per cent, and at certain seasons even exceeds 90 per cent on the Pacific coast. This belt, from which there is a well-marked decrease inland, is in striking contrast with the Western Plateau Province, in the lee of the Pacific coast mountain ranges. The high humidities on the coast remain fairly constant throughout the year. The minima over the Great Basin, on the other hand, become distinctly more marked during the hot summers of that region, reaching 30 per cent and even 20 per cent over the arid or semi-arid lowlands. This seasonal change is clearly indicated in the annual migration of the lines of relative humidity. These travel northward as summer comes on, reach their northernmost limits in June or July, and then return southward again. Some of them even disappear entirely from the map in winter. Another effect of this seasonal variation is seen in the increase in summer of the relative humidity gradient between the damper Pacific coast and the drier interior deserts east of the mountains.

Most of the eastern United States, inland from the coast and east of the Great Plains, averages about 70 to 75 per cent for the year, with comparatively little seasonal variation. The Plateau districts average, as a whole, some 10 to 20 per cent lower, with the seasonal changes just noted. The Plains are intermediate between the damper eastern and the drier Plateau

districts. The distortion of the lines in the vicinity of the Great Lakes shows that these large bodies of water have similar effects to those of the oceans in increasing the relative humidity. This effect can be seen where stations on the lee side of one of the Lakes are compared with others on the windward side. Thus, Grand Haven, Michigan, has a mean annual relative humidity of 78 per cent; Milwaukee, Wisconsin, on the opposite shore of Lake Michigan, has 75 per cent; Davenport, Iowa, and St. Paul, Minnesota, farther west, have 72 per cent.[1] Another interesting fact, illustrating the effect of a mountain barrier upon the relative humidity on the windward and leeward slopes, has been brought out by Day in the monograph already referred to.[2] In the cases of both Mt. Washington, New Hampshire, and Pikes Peak, Colorado, the percentages of relative humidity are continuously high. On the lee sides of these mountains the humidities are comparatively low, the obvious result of loss of moisture in the air passing over the mountains, and of the decrease in humidity due to adiabatic warming of the air descending on the leeward side. High relative humidities are to be expected generally on the windward sides of mountains and low values on the lee sides. These conditions are seen over the eastern sections of Colorado and Wyoming on the winter charts and also, less clearly, in the district just east of the Appalachians.

In both annual and diurnal periods relative humidity is, as a general rule, highest when the temperature is lowest and lowest when the temperature is highest. When the curves are plotted together they are directly the opposite of one another. April is generally the month of lowest relative humidity east of the Rocky Mountains; to the west the midsummer months are driest. Over most of the country the highest relative humidities come in the colder months. In the southeast they may occur in late summer or in early autumn. Elevated areas, as a rule, have comparatively high values without large seasonal and

[1] C. H. Eshleman, "Climatic Effect of the Great Lakes as typified at Grand Haven, Michigan," *Met. Chart of the Great Lakes*, United States Weather Bureau, September, 1913.

[2] P. C. Day, loc. cit., footnote 2, page 270.

diurnal variations. Throughout the year the lowest relative humidity is found in the southwestern interior, and the highest on the north Pacific coast and elsewhere near, and especially to leeward of large bodies of water.

In his description of the climatology of the United States Hann refers to the fact that the air is drier in New England than in western Europe in districts of similar mean annual temperatures, a point first emphasized by Desor.[1] This lower humidity is explained as the result of the prevalence of offshore (northwest) winds in New England in winter. In summer the prevailing winds are also offshore (southwest, west) and are much drier than those of Europe. Again, the annual variation of relative humidity and cloudiness with a winter minimum and a summer maximum that is found on the eastern coast of Asia is not characteristic of the eastern coast of the United States. The prevailing winter offshore winds on the North American Atlantic coast are less emphatic and less regular than those of eastern Asia, being frequently interrupted by damp easterly cyclonic indrafts from the ocean.

Absolute Humidity and its Distribution. The actual amount of water vapor in the air is known as the absolute humidity. It is usually expressed in decimals of inches of pressure, and is then known as vapor pressure. Another way of expressing it is to give the actual weight of the moisture present in the air, as so many grains in a cubic foot, or grams per cubic meter. Climates which are distinctly to be classed as "dry" may have as much water vapor present in their atmosphere as is found in "moist" climates. Desert air is often absolutely moister than the air in a much damper region. On the other hand, as the actual vapor content of the air is frequently of considerable importance in industrial and engineering undertakings, the values of vapor pressure are in many cases of real significance and need consideration in any complete description of climate. It is because of the generally greater meteorological, climatic,

[1] J. Hann, "Handbuch der Klimatologie" (3d ed.), 1911, Vol. 3, pp. 386–387. Desor pointed out in 1852 (*Proc. Boston Soc. Nat. Hist.*, Vol. 4 (1851–1854), pp. 183–184) that because of this condition furniture made in Europe does not hold together well in New England.

and physiological interest in relative humidity that the distribution and variation of absolute humidity have hitherto received the least attention.[1]

Recently, however, the distribution of absolute humidity both in space and in time has been very fully discussed.[2]

Figs. 87 and 88, redrawn from the *Atlas*, show the distribution of absolute humidity over the United States in January and in July. Temperature is the chief control of absolute humidity. Therefore the lines of equal vapor pressure follow the isotherms fairly closely. Other less important controls are the distance from large bodies of water, the wind direction (whether it be from or toward those sources of supply of vapor), and the intervening topography. In midsummer the amount of moisture in the atmosphere is generally from two to four times as large as in midwinter, the seasonal curve of vapor pressure as a rule closely following that of the temperature. In January, with the exception of the warm Gulf coasts, the absolute humidity is low, mainly because of the cold. In

[1] See, for example, H. H. C. Dunwoody, "Absolute Humidity and Mean Cloudiness in the United States represented by Tables and Charts," *Annual Report of the Chief Signal Officer for 1884* (1884), Appendix 9, pp. 128–129 (contains four charts of the seasonal distribution of absolute humidity in grains per cubic foot, based upon the observations for 1883 at regular Signal Service stations). F. H. Bigelow, loc. cit., footnote 1, page 270. A. W. Greely, "American Weather," chap. v (contains Charts XVIII and XIX showing mean absolute humidity in grains per cubic foot for January and July, based on data for 1876–1886). Frank Waldo, "Elementary Meteorology," Figs. 112, 113 (the same charts as those of Greely, just referred to). F. H. Bigelow, "Report on the Temperatures and Vapor Tensions of the United States, reduced to a Homogeneous System of 24 Hourly Observations for the 33-year Interval, 1873–1905," *U. S. Weather Bur. Bull. S* (1909), 302 pages.

[2] P. C. Day, loc. cit., pp. 10–12, Charts 27–34, Figs. 1–6. The charts show the average vapor pressure in inches at 8 A.M. and 8 P.M., 75th-meridian time, for January, April, July, and October, with the corresponding isotherms. The figures show the annual and diurnal march of vapor pressure at several selected stations and the ratios of the mean vapor pressures at 8 A.M. and 8 P.M., 75th-meridian time, to their bi-hourly means for local standard time at three stations. Several of Day's charts, first published in 1917, and a few of the same curves, appear in the section on Precipitation and Humidity of the *Atlas of American Agriculture*. Figs. 102 and 106 in the *Atlas* show the average vapor pressure in inches for January and July, based on the mean of the 8 A.M. and 8 P.M. (75th-meridian time) vapor pressures as observed at about two hundred regular Weather Bureau stations. These means do not differ much from the twenty-four-hour average. Fig. 89 shows, for selected stations, the annual march of vapor pressure; see also text page 45.

fact, it is about the same as that over the interior Plateau in midsummer. The extremes are 0.05 in. in North Dakota, in a district of great cold, and 0.55 in. in Florida, where the temperatures are highest. From the district of minimum moisture there is an increase in all directions, roughly in proportion to the increasing temperatures. In July the Gulf coast again has the maximum (about 0.85 in.), while the minimum (0.25 in.) has shifted from the northern Plains to the interior western Plateau district. Therefore, there is again a close conformity to the distribution of temperature; namely, an increase from north to south, as there is an increase from winter to summer. In southwestern Arizona, a dry desert climate, there is actually more moisture in the air in midsummer than there is in the moist climates around the Great Lakes. In the first-named district, however, the high summer temperatures and the resulting large capacity of the air for water vapor result in a low relative humidity, and the air is therefore dry. In the vicinity of the Great Lakes, on the other hand, with lower temperatures, the relative humidity is much higher than in Arizona, and the air is therefore relatively moist.

The diurnal variations in absolute humidity are chiefly dependent upon local conditions of evaporation from moist surfaces and upon the balance between that source of supply of water vapor and any loss that takes place through condensation (dew, frost, etc.), all these processes being largely under the control of temperature. Minima usually come at night, and maxima by day. All the interacting controls are subject to variations which depend upon permanent local conditions and upon temporary weather types.

Evaporation. Evaporation is an important element of climate, especially in relation to vegetation. It is also a marked control of the amount of water available for water supply and irrigation, and is a determining factor in the matter of physiological comfort or discomfort. The loss of soil moisture by evaporation is often critical for crops, especially in semi-arid and arid regions.

Although there have been numerous studies of evaporation in this country, there is not yet available any general map of

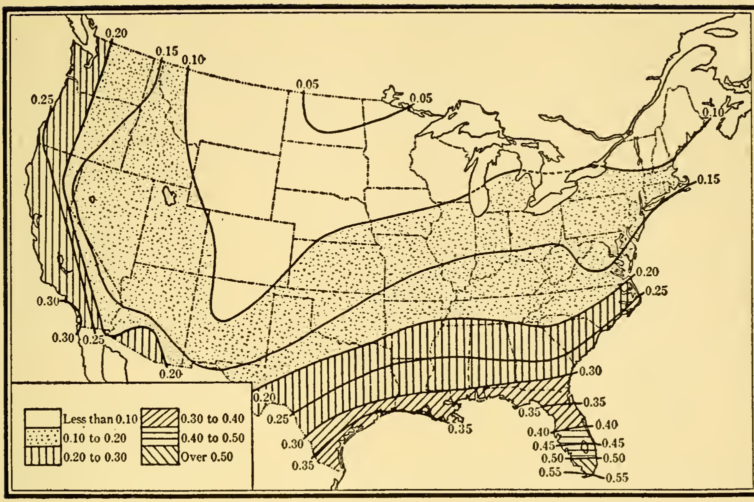

FIG. 87. January Average Vapor Pressure, in Inches

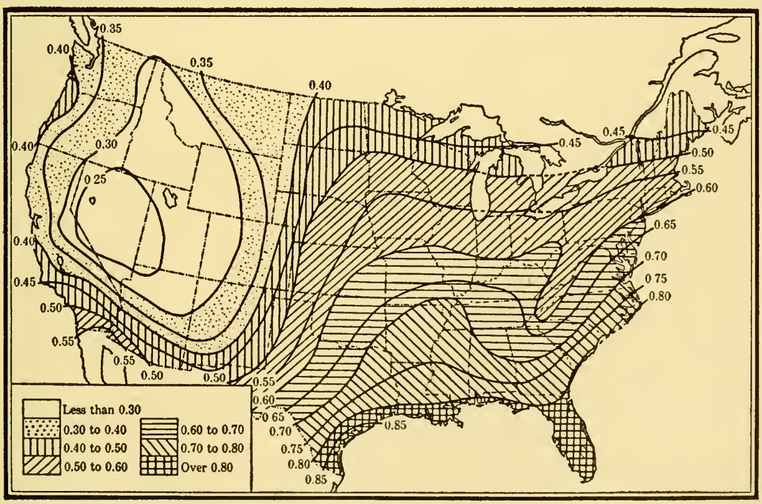

FIG. 88. July Average Vapor Pressure, in Inches

the mean annual amounts of evaporation based on numerous homogeneous and comparable data.[1] The observations during the warm season (April–September) have recently been tabulated, and the values entered on a map of the United States, but owing to the insufficiency of the data no lines of equal amounts of evaporation have been drawn.[2] The observations here used are for evaporation from a free water surface, which, in the absence of sufficient data regarding the loss of soil moisture, may be taken as a fair indication of the relative values of the latter. Other things being equal, evaporation is greatest during the warmer months and is then most critical for agriculture. To a large extent the amount of evaporation determines the "efficiency" of the rainfall. This is particularly true where the mean annual rainfall is barely sufficient for successful agriculture. A fairly good rainfall combined with a large evaporation may be no better for crops than a smaller rainfall combined with less evaporation.

The available data are rather scanty for the eastern United States, but more numerous for the West, especially over the Great Plains. Warm-season evaporation shows a marked increase from north to south over the Plains. It is about twice as large in western Texas (about 50–60 in.) as in western North Dakota (between 30 and 35 in.). In connection with the relation of evaporation and mean annual rainfall it appears that from an agricultural standpoint a 20-inch mean annual rainfall in eastern North Dakota is about equivalent to 30 in. in southern Texas. In the former, wheat, oats, timothy hay, and other crops associated with a "humid type" of agriculture usually have enough moisture where the mean annual rainfall is 20 in. In the parts of Texas where the mean annual rainfall is the same, grazing and drought-resistant crops are found. East of the Mississippi River the warm-season evaporation

[1] For reference to the literature through 1908 see Grace J. Livingston, "An Annotated Bibliography of Evaporation." Reprinted from *M. W. R.* for June, September, and November, 1908, and February–June, 1909, 121 pp. (This is a very useful publication. Later discussions will be found in *M. W. R.* from 1909 to date.)

[2] Precipitation and Humidity section, *Atlas of American Agriculture*, text page 48, Fig. 107, Tables 1–4.

varies considerably (from 25 to about 40 in.).[1] The maximum values are given for southeastern California (80–90 in.).

Near the coasts the loss of water by evaporation is in general probably about equal to or a little less than the gain by rainfall, although there are many local exceptions to this broad statement. In the drier parts of the interior the loss from free water surfaces may be as much as ten times and more the amount of the rainfall.[2]

Sensible Temperatures. It is a matter of common knowledge that the air temperature in the shade, measured by the ordinary dry-bulb thermometer, very often fails to indicate the sensation of comfort or discomfort that human beings actually experience. It is also widely known that the moisture in the air has much to do with the temperature that people feel. When the air is hot and dry, evaporation is rapid. Evaporation involves the expenditure of energy, and this energy often comes, at least in part, from the sensible heat of some adjacent substances. Thus, in the case of the human body on a hot dry day, the evaporation of the perspiration involves taking much sensible heat from the surface of the body, and cooling results. Obviously the greater the evaporation, other things being equal, the more the body cools. When, on the other hand, the air is hot and damp, there is little evaporation, and hence little cooling of the body surface. The air is then "muggy" and oppressive. In cold dry air there is little evaporation, because

[1] Some of the observations cover only one year.

[2] In a paper read before the April, 1921, meeting of the American Meteorological Society, B. C. Kadel presented some results of studies of the evaporation from the Salton Sea, California, which lies in a depression 250 feet below sea level in a region in which the average annual rainfall is less than 3 in. Allowing for inflow, change in area, and rainfall, but not for seepage, the mean annual evaporation for the ten-year period 1910 to 1919 was found to be 69 in. The greatest in any one year was 85 in., in 1915; the least in any one year was 53 in., in 1917. See also A. J. Henry, "Salton Sea and the Rainfall of the Southwest," *M. W. R.*, Vol. 34 (1906), pp. 557–559; F. H. Bigelow, "Studies on the Rate of Evaporation at Reno, Nevada, and in the Salton Sink," *Nat. Geogr. Mag.*, Vol. 19 (1908), pp. 20–28; "Studies on the Phenomena of the Evaporation of Water over Lakes and Reservoirs": II. "The Observations on Evaporation made at the Reservoir in Reno, Nevada, August 1 to September 15, 1907"; III. "Discussion of the Observations made at Reno, Nevada, August 1 to September 15, 1907," ibid., Vol. 36 (1908), pp. 24–39, Charts 17–27 (the author concludes that the evaporation from the Salton Sea may not be more than 4 or 5 feet annually).

air at low temperatures cannot hold much water vapor. Furthermore, the body does not lose as much heat by conduction as when the cold air is damp, damp air being a better conductor than dry air. Hence severe cold in winter is much less chilling when the air is dry than when it is damp.[1]

The fact that the "dry" heat and the "dry" cold of the western interior of the United States are usually much less trying than are the same temperatures in the moister air of the East is traditional, and has been a matter of common report since the early days of white settlement in the West.[2]

The sensation of temperature which human beings experience, for which the term "sensible temperature" has been suggested, is determined by many factors other than air temperature and moisture. Wind velocity, evaporation, direct and reflected sunshine, radiation, also play a part. In addition, many more or less "accidental" factors are concerned, such as the state of health of the individual; clothing; food; kind and conditions of occupation; the mental state; and so on. What we feel, therefore, is the complex resultant of many variables. It is largely a nervous sensation, and therefore differs in different individuals.

Measurement of Sensible Temperatures. It is clearly impossible to measure such a complex sensation precisely and satisfactorily with any of the ordinary meteorological instruments.[3]

[1] For a further discussion of the adjustment of the body to temperature, see R. DeC. Ward, "Sensible Temperatures," *Bull. Amer. Geogr. Soc.*, Vol. 36 (1904), pp. 129–138 (with bibliography).

[2] Blodget observed that "sensible perspiration is rarely experienced in even the warm climate of southern New Mexico," and that "the languor and oppressiveness attending a heat of 90° to 95° in the Eastern states is never felt at such temperatures." He also remarked that the dry winter cold of the interior is more easily borne than damp cold, and recognized the practical consequences of the low relative humidity in the fact that "the valuable grasses" dry "without loss of their nutritive value." The "absence of humidity" was further seen to be "very favorable to observation of astronomical and other instruments" (Lorin Blodget, "Climatology of the United States" (1857), chap. iv).

[3] For a few recent studies of this general subject in its larger climatic relations see E. B. Titchener, "The Psychophysics of Climate," *Amer. Journ. Psychol.*, Vol. 20 (1909), pp. 1–14 (with bibliography); W. F. Tyler, "The Psychophysical Aspects of Climate, with a Theory concerning Intensities of Sensation," *Journ. Trop. Med. and Hyg.*, April 15, 1907; Griffith Taylor, "The Control of Settlement by Humidity and Temperature (with special reference to Australia and the Empire): An Introduction to Comparative Climatology," *Commonwealth Bur. of Met. Bull.*

The dry-bulb thermometer in the shade gives data of the greatest importance in the construction of daily weather maps and in the study of the distribution of pressure and of the general circulation of the atmosphere. To express the cooling effect of evaporation these readings need a "correction." The dry-bulb cannot and is not intended to give a precise indication of the temperature sensation which is experienced by man. The wet-bulb thermometer, because its readings are affected by evaporation, is the meteorological instrument in universal use which comes nearest to giving an index of human comfort and discomfort in so far as these depend upon the temperature and moisture of the air. Yet even the wet-bulb does not give data which are directly comparable with the sensations of cold and heat which the body feels.[1]

Sensible Temperatures in the United States. So far as the climates of the United States are concerned, there have been several studies of this subject. In a pioneer publication (1894) the term "sensible temperature" was used to designate "that which is felt at the surface of the skin, especially where the skin is exposed, on the face and hands," and it was urged that the readings of the wet-bulb thermometer be taken as indicating

No. 14 (Melbourne, 1916), 32 pages ; J. W. Gregory, "The Wet Bulb Thermometer and Tropical Colonization," *Journ. Scot. Met. Soc.*, 3d Ser., Vol. 16 (1914), pp. 3–9; E. Huntington, "Civilization and Climate," 1915. For a description of a new instrument designed to measure the degree of bodily comfort see Leonard Hill, "The Measurement of the Rate of Heat-Loss at Body Temperature by Convection, Radiation, and Evaporation," *Phil. Trans. Roy. Soc.*, London, Series B, Vol. 207 (1916), pp. 183–220; also "Atmospheric Conditions which affect Health," *Quart. Journ. Roy. Met. Soc.*, Vol. 45 (1919), pp. 189–207. Other references on this subject may be found in *M. W. R.*, Vol. 48 (1920), pp. 495–499, 687–690, etc.

[1] Discussing the temperature shown by the dry-bulb thermometer an earlier writer said: "But that temperature! What is it? Is it the temperature we feel when in this arid America we work in our fat fields and burdened orchards in time of harvest? Is it the temperature of our winter days when we walk unfrosted in an air whose breezes stimulate every sense? It is not this temperature. 'It is the temperature of a thread of quicksilver; it is not the temperature of life.' Let others rest content with this temperature of a thing that never had life — that only in mockery is called quicksilver, living silver. We have the right to demand then that all may know day by day what is the sensible temperature — the temperature of the grain that grows, of the fruit that mellows into the very extract of our glorious sun, of the living men and women who are here building empire" (W. A. Glassford, "Why Summer in the apparently Hot Arid Regions is Comfortable," *Monthly Rept. Oregon State Weather Service for January, 1896* (Salem, Oregon, 1896), pp. 23–29).

the temperature of evaporation thus felt.[1] Charts are now available which show the reduction by evaporation of the ordinary (dry-bulb) temperatures and also the sensible temperatures as indicated by the wet-bulb thermometer.[2] The accompanying map is redrawn from one of the three most recent charts dealing with this element of the climates of the United States.[3] These show, for April, July, and October, the average depression of the wet-bulb at the time of minimum relative humidity, which corresponds closely to the time of maximum temperature. The chart here reproduced is that for the midsummer month, July, when the effects of evaporation in lowering temperature are at a maximum for the United States as a whole (Fig. 89).

The essential facts brought out on these various charts can readily be summarized. The cooling effects of evaporation are naturally greatest where and when the air is both warmest and driest. Therefore the high summer temperatures of the drier portions of the country are not as oppressive as the ordinary dry-bulb temperature readings would seem to indicate. During the hottest part of the day in midsummer, as seen on the accompanying map, the reduction of temperature by evaporation is

[1] M. W. Harrington, "Sensible Temperatures," *Int. Med. Mag.*, Vol. 3 (1894), pp. 481–485; also published separately as a paper read before Amer. Climatol. Assoc., Washington, D. C., May, 1894, 7 pages. It should be pointed out that the temperatures of perspiration-evaporation are not identical with the temperatures shown by the wet-bulb thermometer. The latter are only an approximation to the former. From October, 1895, through August, 1899, the wet-bulb readings at regular Weather Bureau stations were printed on the Washington daily weather maps. From October, 1895, through February, 1897, the heading of the column in which the wet-bulb readings were printed was "Sensible (wet thermometer)." On March 1, 1897, the heading became "Wet Bulb." No data for drawing lines of equal wet-bulb temperatures for the different months are now directly available except in the original station records.

[2] M. W. Harrington, loc. cit. (Chart I shows the reduction by evaporation of the mean July temperatures; Chart II shows the sensible temperatures which result from this reduction.) W. L. Moore, "Some Climatic Features of the Arid Regions," *U. S. Weather Bur.* (1896), 19 pages, 2 figs., 3 charts. (Chart I shows the average actual and sensible temperatures for the summer, based on eight years' observations, 8 A.M. and 8 P.M., 75th-meridian time. Chart II shows the mean actual and sensible temperatures for July at 8 P.M., 75th-meridian time.)

[3] Precipitation and Humidity section, *Atlas of American Agriculture*, p. 47; Charts 103–105 (Chart 104 is here reproduced as Fig. 89. These three charts were previously given advance publication by P. C. Day, loc. cit., footnote 2, page 270).

more than 30° in the far Southwest and is more than 20° over practically all the Rocky Mountain and Plateau areas. East of the Great Plains and on the Pacific coast the reduction is much less. It decreases to 10° or 12° along most of the Atlantic coast and to 6° on the north Pacific coast, and at certain stations in the Great Lakes region, not shown in Fig. 89, it is less than 6°.[1]

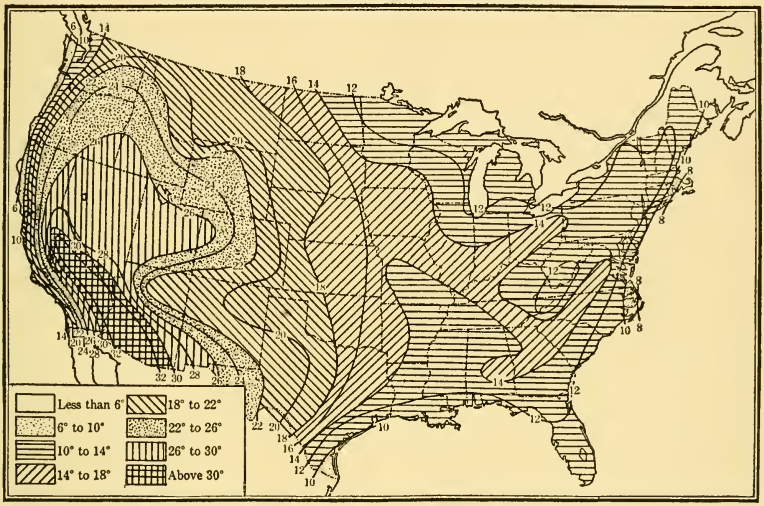

FIG. 89. Average Depression of the Wet-Bulb Temperature at the Time of Minimum Relative Humidity in July

The reduction of temperature by evaporation is obviously less for the whole month of July and for the three summer months than it is for the hottest time of day in July. Over the Plains and the Rocky Mountain area evaporation lowers the *mean* July temperature about 10°–20°; east of the 100th meridian the reduction is mostly 5°–10° except on the immediate Atlantic and Pacific coasts, where it is even less. Southern New Mexico and Arizona in summer have essentially the same

[1] At the time of maximum temperature in spring and fall, the depression of the wet-bulb is several degrees less over the western mountain and plateau area. Elsewhere the seasonal variation is smaller. See Figs. 103 and 105 in the *Atlas of American Agriculture.*

wet-bulb temperatures as those over considerable sections of the Northeast. The northern Pacific coast rejoices in relatively low sensible temperatures. On the other hand, high sensible temperatures are felt along the southern Atlantic and Gulf coasts, where for much of the summer the air is both hot and damp, and hence becomes muggy and oppressive. Over about two thirds of the western arid and semi-arid regions the temperature of evaporation during the summer is below 55°, and over almost one third it is not over 50°. East of the 105th meridian the average sensible temperature in summer ranges between 55° and 75°.

The adjustment of the human body to high temperatures may be furthered in several ways. The direct rays of the sun should be avoided. The clothing should be light and loose to allow free passage of air and of moisture. The use of electric fans to increase the air movement and thus to promote evaporation is another simple and effective means of obtaining added comfort in a hot climate.

CHAPTER XIII

SUNSHINE, CLOUDINESS, AND FOG

SUNSHINE AND SUNSHINE CHARTS · DISTRIBUTION OF SUNSHINE: GEOGRAPHICAL AND SEASONAL · CLOUDINESS AND MAN · CLOUDINESS AS A CLIMATIC ELEMENT · MEAN ANNUAL CLOUDINESS · SEASONAL VARIATIONS IN CLOUDINESS · RELATION OF CLOUDINESS TO RAINFALL · DISTRIBUTION OF CLEAR, PARTLY CLOUDY, AND CLOUDY DAYS · FOG IN GENERAL · GEOGRAPHICAL DISTRIBUTION OF FOG · INLAND FOGS DUE TO RADIATION · INLAND FOGS DUE TO CYCLONIC CONDITIONS · MARINE FOGS IN GENERAL · PACIFIC COAST FOGS · ATLANTIC AND GULF COAST FOGS · FOGS OF THE GREAT LAKES · "DARK DAYS"

Sunshine and Sunshine Charts. Sunshine is the complement of cloudiness. The relation is simple: the more cloud the less sunshine, and vice versa. If, therefore, the mean monthly or mean annual percentages of cloudiness be subtracted from 100, the remainders should give the amounts of sunshine in percentages of the possible duration. Similarly, if the possible duration of sunshine (in percentages) be subtracted from 100, the remainder should give the mean cloudiness. These results are, however, only approximate. They may and often do differ more or less from the instrumental results obtained by means of sunshine recorders. For example, bright sunshine may be recorded for hours while the sky is noted as being "cloudy" with a cirro-stratus cover. The amount of cloudiness is based upon estimates made by eye at certain stated hours during the day. Such estimates are inevitably more or less inaccurate and individual, and are difficult to make when the clouds are near the horizon. Sunshine recorders on the other hand, while they give a rigidly instrumental record of the duration of bright sunshine, include only a small portion of the sky and are also less reliable when the sun is low and its rays are weak. These intrinsic sources of inaccuracy do not, however, in any way

seriously interfere with the value of the ordinary sunshine data which are available for many parts of the world.

Sunshine charts are of two classes. They either (1) give the number of hours of bright sunshine as determined by means of sunshine recorders or (2) they show the duration of sunshine in percentages of the possible duration. These percentages may be obtained from the cloudiness estimated by eye at regular hours, or by comparing the total number of hours of bright sunshine as indicated by sunshine recorders with the total possible number of hours, and expressing the results as percentages. When eye observations of cloudiness are available, but sufficient instrumental records of sunshine are lacking, the former method is the one naturally adopted. Sunshine charts of both kinds have been published for the United States.[1] Each of the methods of presenting sunshine data has its advantages, and both are employed in the latest series of charts, prepared by Kincer.[2]

Distribution of Sunshine: Geographical and Seasonal. The map (Fig. 90) shows the distribution of sunshine for the year, expressed in percentages of the possible amount. The latter is essentially the same for all parts of the country. The maximum percentage of sunshine (over 85 per cent) is in the extreme southwestern interior. This has been called the "sunshine center" of the United States.[3] The minimum (under 40 per cent) is along the northern Pacific coast. The lake region, the northern and central portions of the Appalachian area, and the Northeast have slightly higher percentages (from 45 to 50 per cent). Elsewhere east of the Mississippi River and over

[1] See R. DeC. Ward, "Bibliographic Note on Sunshine in the United States," *M. W. R.*, Vol. 47 (1919), pp. 794–795.

[2] Sunshine and Wind section of the *Atlas of American Agriculture*. See also J. B. Kincer, "Sunshine in the United States," *M. W. R.*, Vol. 48 (1920), pp. 12–17, 9 figs. (Fig. 90, below, is reproduced from the corresponding chart (Fig. 1) in this paper. The basic data are for the uniform period of twenty years (1895–1914). The percentages of the possible amounts are for the eight-year period 1905–1912).

[3] "Sunshine runs into dollars and cents in this region because the line of '80 per cent sunshine,' or perhaps the slightly larger 75 per cent line, may be said to inclose the section of the United States which sells its climate on a year-round basis to thousands of tourists, outdoor enthusiasts, and health-seekers" (*News Bulletin*, National Geographic Society, 1924).

the northern tier of states from the upper Great Lakes westward to the Rockies, the percentages range from 50 to 60. They are somewhat higher in the Southeast, especially in the Florida peninsula.[1] Between the Mississippi River and the Rocky Mountains the annual percentage is generally between 60 and 70, and the same values hold for the central Rocky Mountain region and northern Plateau states. There is thus

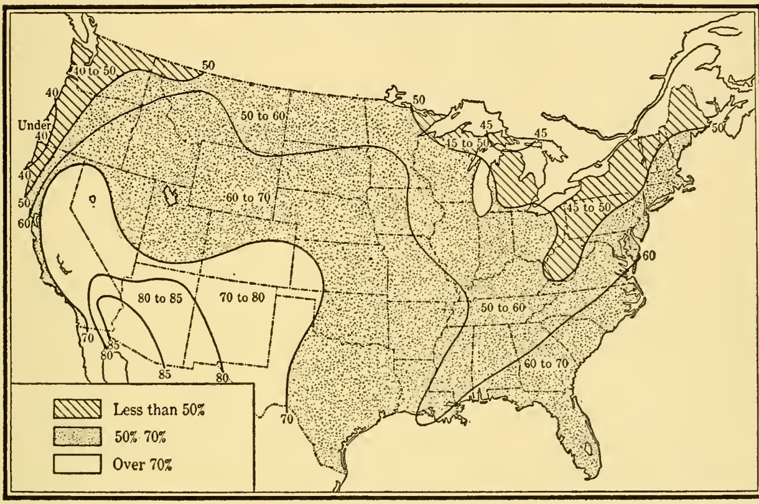

FIG. 90. Mean Annual Sunshine, in Percentages of the Possible Amount

seen to be a decrease in the amount of sunshine from the southwestern interior to the northwest, north, and northeast and, to a less degree, to the east. For the United States as a whole the average annual amount of sunshine is about 60 per cent of the possible amount.

The sunshine conditions for the four seasons, given in percentages of the possible, show for the country as a whole 48 per cent in winter, 60 per cent in spring, 68 per cent in summer, and 60 per cent in autumn.[2] The maximum seasonal amount of

[1] "Here again sunshine means dollars and cents for Miami and Palm Beach and their fellow resorts" (ibid.).

[2] Sunshine and Wind section of the *Atlas of American Agriculture*, Figs. 102–105.

sunshine is 95 per cent—in the valley of California in summer. The minimum amount is under 30 per cent over the Northwest in winter. The annual variation is greatest in the Northwest and over the Lakes. Both these regions have marked seasonal variations in cyclonic activity, and both have marked effects of water areas upon the moisture content of the prevailing winds. The charts showing the average number of hours of bright sunshine daily, by months, indicate quite emphatically the general northward migration of summer conditions, with more sunshine as the season advances from the colder to the warmer months.[1] The summer months are the sunniest in most sections, whereas spring and autumn have the most sunshine over certain smaller areas. July is the time of maximum sunshine over about half the country. The increase in the amount of sunshine from winter to summer is very marked over the northern portion of the United States.

For the country as a whole there is less sunshine in the early morning hours, a maximum near noon, and a secondary minimum in the late afternoon. This general rule, and the departures from it, may be explained by the conditions of local cloud or fog formation.

Many interesting comparisons suggest themselves as regards sunshine between Europe and the United States. The contrast between western Europe and eastern North America was clearly emphasized by Woeikof a number of years ago.[2] He pointed out that the American coast has great advantages in respect to sunshine, especially if stations having similar temperatures are considered and not stations in the same latitudes. "Not only is the duration of sunshine longer (on the American coast) but the air is clearer, especially in the colder months. This contrast is very strikingly emphasized on the voyage from England to the United States."

Cloudiness and Man. The amount of cloudiness affects man in many ways. In summer, cloudy days provide protection from the sun's rays; in winter, cloudy skies at night diminish nocturnal radiation, check the fall of temperature, and thereby

[1] Sunshine and Wind section of the *Atlas of American Agriculture*, Figs. 90–101.
[2] A. Woeikof, "Die Klimate der Erde" (1887), Part II, p. 45.

reduce somewhat the need of fuel for heating purposes. Clear, calm winter nights are usually the coldest. On the other hand, dark, overcast days in winter often seem colder than they really are because of their lack of sunshine. Such days necessitate an increased use of artificial light and hence of fuel for power purposes. The amount of cloud has distinct psychological effects. Continuously gray skies are depressing. Bright, sunny climates tend to make people cheerful. Steadily cloudless skies, on the other hand, easily become monotonous. The continued glare of the sun is tiring to the eyes, and one longs for clouds. The amount of cloud controls the duration of sunshine, the brightness of the sky, and the amount of diffused daylight. All these conditions have important relations to the distribution and growth of vegetation and to the development of microörganisms. Medical climatology is closely concerned with cloudiness and sunshine in relation to health and disease. It is significant that the abundant sunshine of California receives so much emphasis in the trade-names of her products. The "Sunshine State" is a favorite designation for California among her people.[1]

The thickness and kind of cloud, as well as the amount, are important. There is a great difference between the effect, psychological as well as economic, of a thin sheet of high cloud, like cirro-stratus, and of a low, dark cloud layer of strato-cumulus or nimbus. A sky largely covered with fine-weather cumulus on a summer day makes a wholly different impression from that given by a stratus cloud-sheet covering an equal portion of the sky.

Cloudiness as a Climatic Element. The amount of cloudiness is recorded by eye on a scale of 0 (cloudless) to 10 (overcast), and the conventional climatic summary includes the mean annual and mean monthly amounts of cloudiness expressed in tenths or percentages. These means, while giving the larger facts that are quite sufficient in general climatic descriptions, do not furnish as vivid a picture of the nature and of the variations of cloudiness as is often desired in detailed studies of

[1] See A. H. Palmer, "The Agricultural Significance of Sunshine as illustrated in California," *M. W. R.*, Vol. 48 (1920), pp. 151–154.

local climates. For such investigations information regarding the average numbers of clear, partly cloudy, and cloudy days in each month should be included. This gives a more complete picture of the actual distribution of cloud and sunshine than do the monthly and annual means. It shows what kinds of days prevail throughout the year.[1] Further, if three observations of cloudiness are taken daily it is very desirable to have the means for the morning, afternoon, and evening hours given separately. In this way the diurnal variation of cloudiness can be readily seen. Two places may have exactly the same mean monthly cloudiness with quite a different diurnal distribution in the two cases. One of them, for example, may have prevailingly overcast skies in the mornings and evenings with cloudless noon hours, whereas the other is partly cloudy all day. The economic and physiological effects of the two climates may differ greatly.

In a broad view of the climates of an extended area like that of the United States it is sufficient if the larger facts of annual and monthly amounts of cloud are known. Details may easily be looked up if they are desired.[2]

[1] Observations covering this aspect of cloudiness are regularly published by the United States Weather Bureau in the *Climatological Data* of the various sections, in the *Monthly Weather Review*, and in the *Annual Reports of the Chief of the Weather Bureau*. Practically no records of nighttime cloudiness are available. Eye observations of cloudiness are made hourly at the central office of the United States Weather Bureau by watchmen, and irregularly at other Weather Bureau stations. Some astronomical observatories also keep records of night cloudiness. The only automatic records of night cloudiness made in the United States are taken at Blue Hill Observatory (Harvard University) and at the University of Chicago station of the United States Weather Bureau. The instruments used are modified Pickering Pole-Star (photographic) recorders. The apparatus at Chicago was most recently installed (described in *M.W.R.*, Vol. 47 (1919), pp. 154–155).

[2] The first monthly and annual cloudiness maps for the United States were included in Teisserenc de Bort's isonephs for the world (1884) and were necessarily based on very incomplete data (Léon Teisserenc de Bort, "Étude sur la Distribution moyenne de la Nebulosité à la Surface du Globe d'après les premières Cartes d'Isonephes," *Annales Bur. Central Météorol. de France*, Vol. 4 (1884)). The data for the United States were those for ninety-six stations, for the period 1843–1854, originally published in the *Army Meteorological Register*. These maps are reproduced in colors in the *Atlas of Meteorology*, Plates 17 and 18, text page 16, the annual map for the United States having been revised by the incorporation of more recent data included in the *Annual Report of the Chief of the Weather Bureau for 1896–1897*. The first complete set of monthly cloud maps for the United States alone was published by General A. W. Greely, then Chief

Mean Annual Cloudiness. The accompanying map of mean annual cloudiness (Fig. 91) was drawn on the basis of data supplied by the courtesy of the Weather Bureau.[1] In drawing the isonephs somewhat greater weight was laid on the data for stations with the longer periods of observations. In dealing with the element of cloudiness, however, the amounts of which are estimated by eye, perfect accuracy is obviously impossible of attainment. It appears on investigation that short-period

Signal Officer, in 1891 (A. W. Greely, "Charts showing the Average Monthly Cloudiness for the United States," *U. S. Signal Service*, 1891). These maps were based on data collected by the Signal Service. The longest period covered by the observations was eighteen years (1871–1888), and many of the one hundred and forty-three stations had shorter records. A discussion of the facts brought out on General Greely's maps was later published by Köppen (W. Köppen, "Regenwahrscheinlichkeit und Bewölkung in den Vereinigten Staaten von Nordamerika," *Met. Zeitschr.*, Vol. 10 (1893), pp. 161–168), who also constructed a series of diagrams showing the annual variation of cloudiness for latitudes 32°, 40°, and 47° N., for longitudes 87° and 97° W., and for the Atlantic and Pacific coasts. The first map of mean annual cloudiness for the United States alone was that published in the *Annual Report of the Chief of the Weather Bureau for 1896–1897* (Part VI, Chart XX, text pages 286–287).

A new series of maps, both monthly and annual, appeared in 1911. These were constructed by K. McR. Clark, then a student in Harvard University (K. McR. Clark, "A New Set of Cloudiness Charts for the United States," *Quart. Journ. Roy. Met. Soc.*, Vol. 37 (1911), pp. 169–175). Observations were used from 77 stations with records for thirty or more years, 31 with less than ten years, and 15 with five years or less. The isonephs were intentionally generalized so as to bring out only the larger facts. In 1912 another and still more complete set of maps and diagrams, prepared by Gläser, was published (Arthur Gläser, "Bewölkungsverhältnisse und Sonnenscheindauer von Nordamerika," *Aus dem Archiv der Deutschen Seewarte*, Vol. 35 (1912), No. 1, pp. 1–63). A very complete discussion of the cloudiness and sunshine of the United States. General Greely's maps were revised by the inclusion of newer and more complete data covering the year 1906, there being 236 stations in all used. There are maps showing annual, seasonal, and monthly isonephs; the annual range in cloudiness; seasons of maximum and of minimum cloudiness; and isopleths for latitudes 32°, 40°, and 47° N., for longitudes 80°, 90°, 100°, and 110° W., and for the Atlantic and Pacific coasts.

For further brief discussions of cloudiness in the United States see A. W. Greely, "American Weather," pp. 64–68 (gives maps of mean cloudiness for January and August on the basis of observations for 1871–1886, also curves showing the annual fluctuations of cloudiness at selected stations); Frank Waldo, "Elementary Meteorology," pp. 352–354 (reproduces Greely's maps for January and August); J. Hann, "Handbuch der Klimatologie" (3d ed.), 1911, Vol. 3, pp. 390–391; F. L. Wachenheim, "Die Hydrometeore des gemässigten Nordamerika," *Met. Zeitschr.*, Vol. 22 (1905), pp. 193–211 (with monthly percentages for selected districts).

[1] The total number of stations employed was about 190. Of these, 65 had over forty years of observations, nearly 40 had between thirty and forty years, 30 had from twenty to thirty years, 40 had from ten to twenty years, and the remainder had ten years or less.

means do not depart to any considerable degree from long-period means. Indeed, the departures are probably no greater than the differences resulting from the personal equation in the case of different observers. It is therefore unnecessary to reduce the means of cloudiness to the same period of time, as is done in the case of instrumental records. Furthermore, the short-period records are by no means to be disregarded as

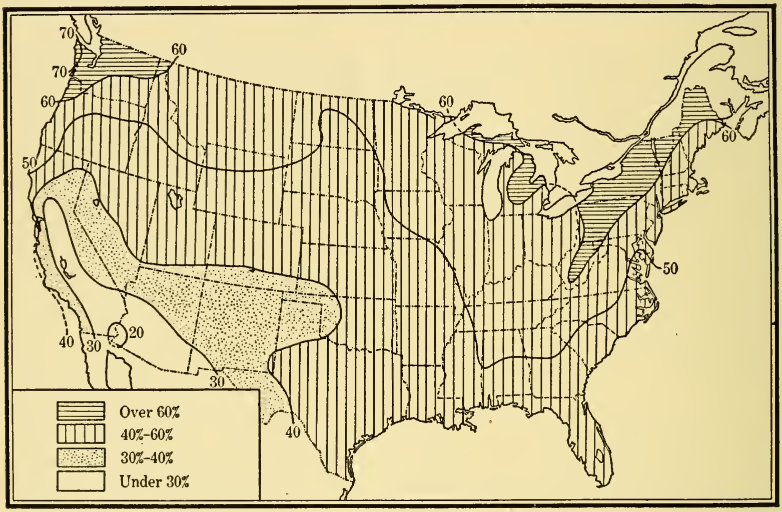

FIG. 91. Mean Annual Cloudiness

altogether unreliable. The accompanying map is intentionally generalized. It is designed to present the larger facts in the distribution of the mean annual cloudiness and not to emphasize details. The isonephs were first drawn on a large-scale map with careful attention to the actual data. They were then transferred to a small-scale map and smoothed. In several cases in which a single station showed a slightly greater or smaller amount of cloudiness than the surrounding sections that station was deliberately omitted in order not to over-emphasize local conditions.[1] In drawing isonephs for as large

[1] For example, in the Appalachian area, in an extended region having as a whole between 50 and 60 per cent, Elkins, West Virginia, with a twenty-year record, has 63 per cent; Wytheville, Virginia (sixteen years), has 46 per cent; Reading,

an area as that of the United States, with the relatively small number of stations for which records are available, a good deal must be left to the individual judgment of the investigator and to his desire to present either a more detailed picture or one more broadly generalized.

If details are omitted and only the larger facts are kept in view, the general distribution of cloudiness for the year is easily described and remembered. There are two districts of maximum cloudiness (over 60 per cent), one lying over most of the Great Lakes region and extending northeastward over the St. Lawrence valley and northern New England; the other found on the extreme northwestern Pacific coast. Both these sections are under marked cyclonic control, especially in the colder months. In both cases the prevailing winds in general blow across bodies of water.[1] Although the available data are rather incomplete, it seems probable that a condition of considerable cloudiness (about 60 per cent or slightly more) is characteristic of a belt of country just to windward of the crest of the Appalachians from northern Pennsylvania at least into West Virginia. On the Pacific slope the presence of mountains close to the coast is an important factor in causing condensation. It is significant that in this last-named section the areas of maximum cloudiness and of maximum rainfall correspond closely. The southwestern portion of the Plateau Province is the least cloudy section of the country. Southern Arizona and the central and southeastern parts of California have less than 30 per cent. A smaller area centered around Yuma,

Pennsylvania (six years), has 60 per cent; Harrisburg, Pennsylvania (thirty years), has 56 per cent; Walla Walla, Washington (thirty-one years), has 50 per cent; and Havre, North Dakota (thirty-six years), has 49 per cent in a general area having between 50 and 60 per cent. Green Bay, Wisconsin (thirty-two years), has 64 per cent in a general area with from 50 to 60 per cent.

[1] "Whenever winds from the Lake strike a cold shore, the relative humidity increases and if the change is great enough cloudiness and precipitation occur. When, on the other hand, the winds strike a warm shore they are warmed, the humidity decreases and the cloudiness dissipates. Hence there is a resemblance to the wet and dry conditions of the Pacific coast" (C. H. Eshleman, "Climatic Effect of the Great Lakes as typified at Grand Haven, Michigan," *Met'l Chart of the Great Lakes*, September, 1913 (United States Weather Bureau)). For further details regarding cloudiness in the vicinity of the Great Lakes see E. S. Clowes, "Cloudiness in New York State," *M. W. R.*, Vol. 48 (1920), pp. 213–214.

Arizona, has less than 20 per cent. The sunny skies of the Southwest are easily explained. Few general storms frequent that part of the country, and it is well shut off from moisture-bearing winds. In going eastward from the southern California coast into the desert there is a marked and rapid decrease in cloudiness.

In general the eastern half of the country has more than 50 per cent, and the western half (except on the north Pacific coast) has less. The Northern states are more cloudy than the Southern states, as is to be expected from the more active and more frequent storm control in the North. This difference is well marked on the Pacific coast and over the Plateau; it is less so in the East. The Pacific coast as a whole is less cloudy than the Atlantic, but the northern part of the Pacific coast is more cloudy than any portion of the Atlantic. Over thirty years ago Woeikof called attention to the fact that although the available data on cloudiness for the eastern United States were then scattering and unsatisfactory, it was already certain that the mean annual cloudiness is less here than in Europe, excepting in the Mediterranean area.[1]

Seasonal Variations in Cloudiness. The mean annual amount of cloudiness, the distribution of which has just been considered, is the result of the interaction of all the cloud-producing conditions working together throughout the year. As these conditions vary more or less in the different months, the average percentage of cloudiness for the whole year gives a very inadequate, and not infrequently quite a misleading, impression of the state of the sky as this is actually seen from day to day and from month to month. If the monthly maps of isonephs are examined, a general but somewhat irregular seasonal migration of the lines of equal cloudiness becomes apparent. Taking the country as a whole, winter is the cloudiest season and summer the clearest. Roughly, from midsummer to early winter there is an equatorward movement of the belt of maximum cloudiness, and from midwinter to summer there is a general northward retreat. This seasonal movement of the

[1] A. Woeikof, "Die Klimate der Erde" (1887), Part II, p. 45.

isonephs is associated with the corresponding equatorward and poleward migration of the general storm belt, and the latter in turn depends upon the seasonal changes of temperature. In winter, general storms are more frequent, better developed, and affect larger sections of the country. This involves the development of more frequent and more extended cloud-sheets. Furthermore, during the colder months, winds which blow from warm waters naturally tend to become cloudy and rainy as they pass over the colder land to leeward. During the winter the Great Lakes and the north Pacific coast have a mean monthly cloudiness of more than 70 per cent and even of more than 80 per cent over smaller areas. The lee shores of the Great Lakes are more cloudy than those to windward. In summer these same sections (the Great Lakes and the north Pacific coast) have, in general, about 50 per cent or less. An exception is a narrow strip on the coast of Washington, which even in summer maintains a mean cloudiness of over 60 per cent.

In the Southwest the area of minimum cloudiness shows a gradual expansion northward and eastward as the season advances. The 30-per-cent isoneph, which incloses a relatively small area in the extreme southwestern interior in winter, covers most of the interior Plateau Province by midsummer, when the 20-per-cent and 10-per-cent lines, which do not appear at all on the winter maps, inclose considerable portions of that same district.

There are certain exceptions to the general rule above stated, that winter is the cloudiest season and summer the clearest. The Pacific coast distinctly shows the contrast between the cloudier skies of its winter and the clearer skies of its summer and early fall. Figs. 92, 93, and 94 show the characteristic seasonal distribution of cloudiness on the Pacific coast and also the gradual decrease in the amount of cloud from north to south.[1] There the season of rain and the season of maximum

[1] In these and the following figures the curve showing the annual variation of cloudiness is based on the mean monthly cloudiness as determined by combining the data for a group of stations in that particular section. The curves are therefore composites.

cloudiness go closely hand in hand. In the valley of California the midsummer months are, indeed, almost cloudless as well as rainless, thus providing most favorable conditions for many outdoor occupations; such, for example, as the sun-drying of

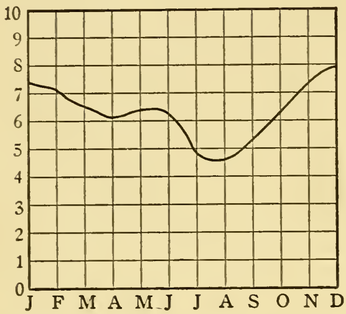

FIG. 92. Annual Variation of Cloudiness, North Pacific Province

Annual mean, 6.3

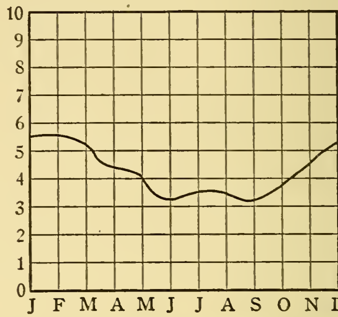

FIG. 93. Annual Variation of Cloudiness, Central Pacific Coast

Annual mean, 4.4

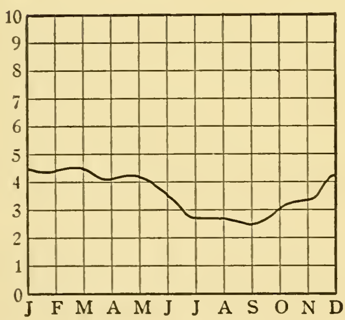

FIG. 94. Annual Variation of Cloudiness, South Pacific Province

Annual mean, 3.6

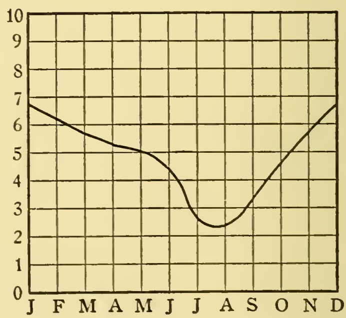

FIG. 95. Annual Variation of Cloudiness, Northern Plateau Province

Annual mean, 5.0

raisins. Over the northern tier of states as a whole, from the Pacific to the Atlantic, July and August (or September) are the least cloudy months. Figs. 95–99 illustrate the annual variation of cloudiness over the states from the Northern Plateau Province eastward to the lower Great Lakes. New England

(Fig. 100) has very little variation in cloudiness through the year. The southern tier of states, on the other hand, with a few exceptions, has its minimum cloudiness in autumn, October being generally the least cloudy month (Figs. 101–103). These

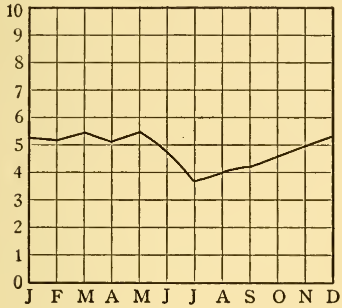

FIG 96. Annual Variation of Cloudiness, Northwestern Plains States

Annual Mean, 4.8

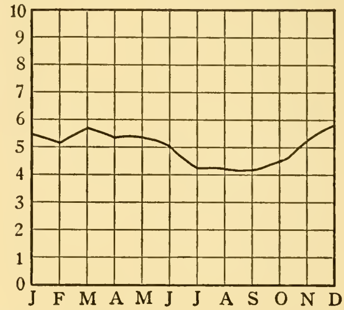

FIG. 97. Annual Variation of Cloudiness, Upper Mississippi Valley

Annual mean, 5.0

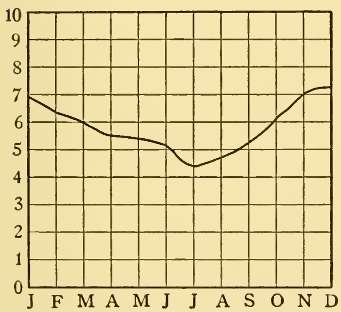

FIG. 98. Annual Variation of Cloudiness, Upper Lakes District

Annual mean, 5.8

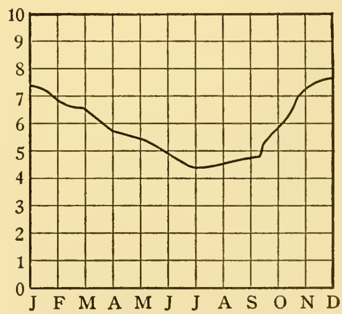

FIG. 99. Annual Variation of Cloudiness, Lower Lakes District

Annual mean, 6.0

autumn months are a transition season before the winter storm control sets in, and are also a time of minimum rainfall over a considerable portion of the eastern United States.

The winter (December–February) maximum of cloudiness is characteristic of the Pacific slope (Figs. 92–94), the Plateau

(Figs. 95 and 104), and all of the southern and eastern United States excepting Florida. The northernmost tier of states east of the Great Plains, including most of the upper Great Lakes region and New England, has its maximum in late autumn or

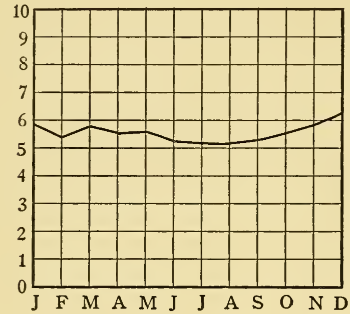

FIG. 100. Annual Variation of Cloudiness, New England States

Annual mean, 5.5

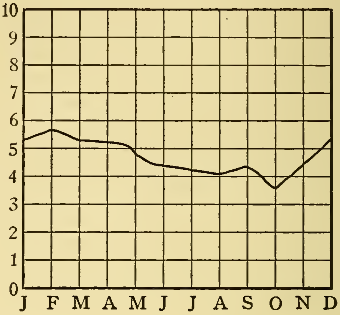

FIG. 101. Annual Variation of Cloudiness, West Gulf States

Annual mean, 4.7

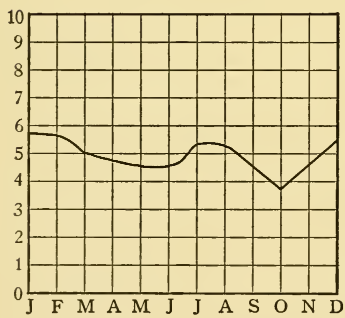

FIG. 102. Annual Variation of Cloudiness, East Gulf States

Annual mean, 5.0

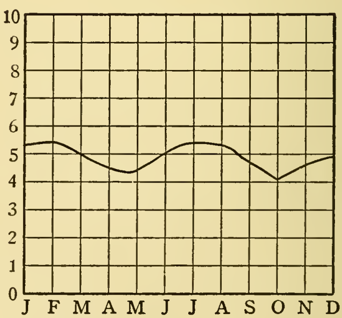

FIG. 103. Annual Variation of Cloudiness, South Atlantic States

Annual mean, 4.8

in early winter (Figs. 97–100). Middle or late spring is the cloudiest season over the northern Great Plains, when the rainfall maximum of that section is already well marked (Figs. 96 and 105). The middle and late summer convectional rains of the southern Plateau, with prevailing southerly winds, give a maximum, or at least a secondary maximum, there in

July and August (Fig. 106). In Florida, also, the summer months with their heavy rainfalls are the cloudiest season (Fig. 107).

Over most of the country the difference between the amount of cloud in the cloudiest and in the least cloudy months is so

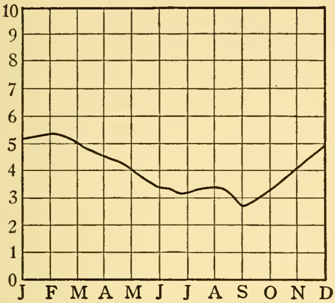

FIG. 104. Annual Variation of Cloudiness, Middle Plateau District

Annual mean, 4.0

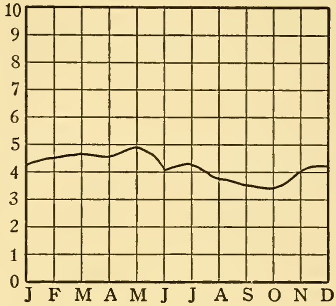

FIG. 105. Annual Variation of Cloudiness, Central Plains States

Annual mean, 4.1

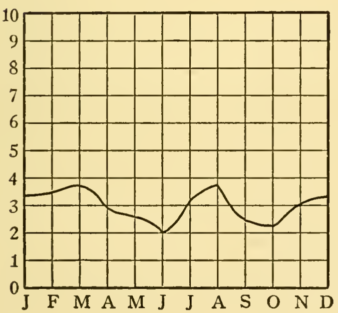

FIG. 106. Annual Variation of Cloudiness, Southern Plateau Province

Annual mean, 3.0

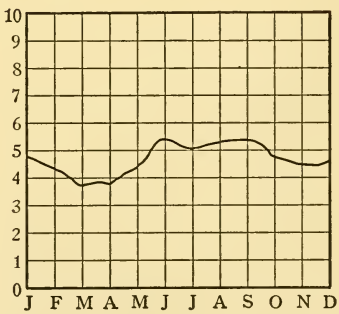

FIG. 107. Annual Variation of Cloudiness, Florida Peninsula

Annual mean, 4.6

small (generally 10–20 per cent) as to be of no special significance. In the two districts of maximum annual cloudiness, the Great Lakes and the north Pacific coast, there is a greater difference (30 per cent or more) between the percentages of cloudiness at the times of maximum and minimum. The

western Plateau also has a marked contrast (30–40 per cent and over) between its cloudy and its clear seasons. The summers are there very sunny, but the winter storms, passing over this district from the Pacific, cause a fair amount of cloudiness. Woeikof seems to have been the first to point out that the annual variation in cloudiness in the central and eastern portions of the United States is less than that in Europe,[1] and Hann called attention to the fact that there is no such well-marked annual variation in the eastern United States as there is in eastern Asia.[2] The reason is found in the frequency of damp easterly cyclonic winds during the American winters, while in eastern Asia the dry offshore northwesterly winds are the dominant winter characteristic and give clear skies.

Relation of Cloudiness to Rainfall. Another matter which also deserves mention here was emphasized by General Greely in his discussion of his monthly cloudiness maps.[3] The annual amounts of rainfall and of cloudiness show no fairly fixed ratio, as might at first be expected. In comparing the southern Great Plains and their relatively small amount of cloud with the cloudier and rainier Great Lakes region, cloudiness and rainfall may seem somewhat closely related. In going east from the northern Great Plains to the Great Lakes, on the other hand, the rainfall doubles, while there is no correspondingly marked increase in the amount of cloud; and the Northern Gulf Province has about four times the rainfall of New Mexico, while the cloudiness in the former district is not even double that in the latter.

Distribution of Clear, Partly Cloudy, and Cloudy Days. The character of a climate in so far as its general relations to cloudiness and to sunshine are concerned may conveniently be judged by the number of its clear days and of its cloudy days. Fewer than 100 clear days a year are usually experienced in the lake region and on the northern Pacific coast, both districts of much storm activity and both exposed to damp winds coming over water bodies (Fig. 108).[4] In the southwestern interior, on the other hand, well inclosed from the sea and far away from the

[1] A. Woeikof, loc. cit. in footnote 1, page 296. [2] J. Hann, loc. cit. in footnote 2, page 292. [3] A. W. Greely, loc. cit. in footnote 2, page 292.

[4] Figs. 108 and 109 are redrawn from Figs. 83 and 84 in the Precipitation and Humidity section of the *Atlas of American Agriculture*.

usual storm tracks, there is an average of more than 300 clear days a year, or the equivalent of ten months. Cloudy days average 160 (over five months) in northernmost Michigan and 180 (six months) on the northernmost Pacific coast (Fig. 109), whereas fewer than 20 days (three weeks) are as a rule cloudy in extreme southwestern Arizona and southeastern California.

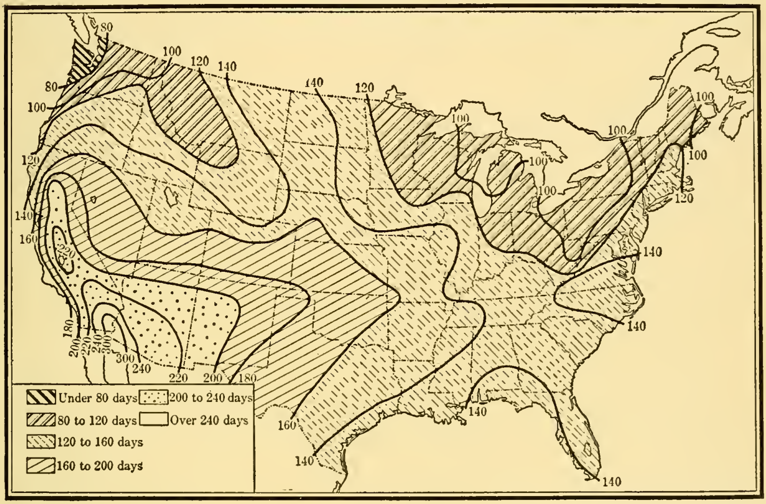

FIG. 108. Average Annual Number of Clear Days

The annual percentages of clear, partly cloudy, and cloudy days have also been charted.[1] The percentage of clear days ranges from about 20 to 25 per cent on the northern Pacific coast and over the lake region to over 90 per cent in the extreme southwestern interior—in southeastern California and southwestern Arizona. On the other hand, the percentage of cloudy days is at a minimum (5 per cent) in the last-named district and at a maximum (over 40 per cent) in the other two areas.[2]

[1] Sunshine and Wind section of the *Atlas of American Agriculture.*

[2] "The 'cloud center' of the United States is in a little region in western Washington. About the little center is a large area of only slightly less marked cloudiness. . . . The cloudiness in this case is accompanied by heavy rain and snowfall, and these, with the high mountains of the region, furnish the ingredients which give the state of Washington a greater potential water power than that of any other state in the Union" (*News Bulletin,* National Geographic Society, 1924).

Fog in General. Silent in its formation and disappearance; unaccompanied by violent atmospheric disturbances of any sort; associated with no brilliant optical phenomena; suggesting no startling world-wide human responses, fog nevertheless has many important relations to the life of man. Ocean fogs delay voyages and lead to collisions and wrecks. On land, fogs shut out sunshine and retard railroad and other means of

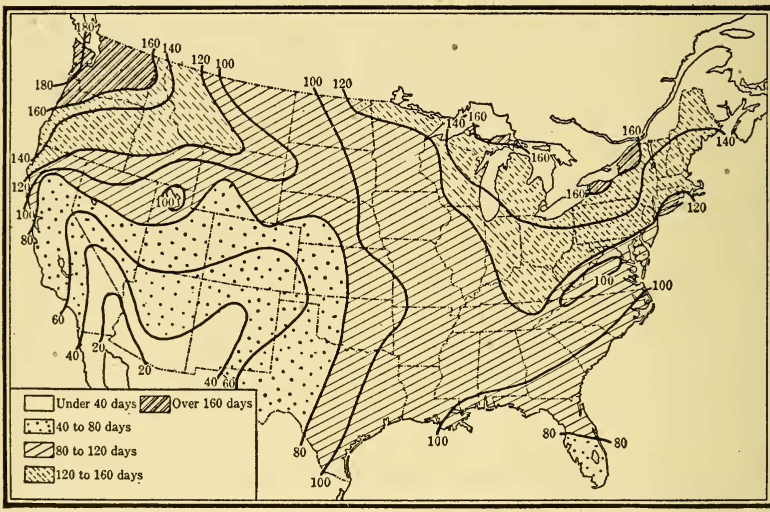

FIG. 109. Average Annual Number of Cloudy Days

transportation. In large cities, especially when fogs are combined with soot and other impurities, they cause much added expense for artificial light and affect business activity along many lines. Doubtless, also, in ways which are not yet definitely established, frequent and long-continued fogs have relations to human health as well as to human comfort. Yet fogs are not without their advantages. Coast fogs on hot summer days may be welcome because of the screen which they provide against the sun's rays. The dampness and sometimes even the very slight precipitation associated with fogs may furnish much-needed moisture to vegetation. As characteristic features of the climate in many parts of the country, fogs merit consideration.

Geographical Distribution of Fog. The United States Weather Bureau recognizes two grades of fog: a fog which obscures objects at a distance of 1000 feet is recorded as *dense*; other fogs are *light*. The geographical distribution of fog in the United States is shown on the accompanying map (Fig. 110).[1] The average numbers of days with dense fog are based on observations at regular Weather Bureau stations during the

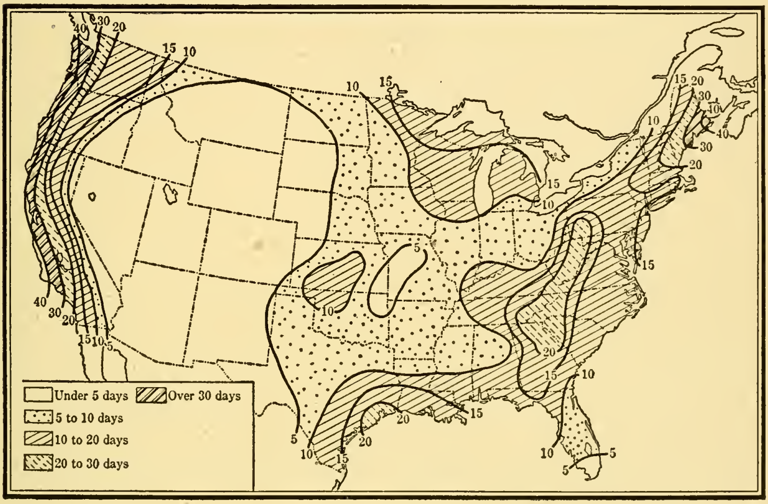

FIG. 110. Average Annual Number of Days with Dense Fog

twenty-year period 1895–1914. The two districts of maximum fog frequency are found along a considerable stretch of the Pacific coast and over the northernmost section of the Atlantic coast. An average of forty days a year with dense fog occurs along the Pacific coast as far as southern California, while the same number of foggy days on the Atlantic is found only at the tip end of the northeastern coast of Maine. The west coast, with its prevailing onshore winds, is thus distinctly foggier than the east coast, where the winds are most of the time offshore. The Great Lakes evidently have no very marked

[1] Redrawn from Fig. 82 in the Precipitation and Humidity section of the *Atlas of American Agriculture.*

effect in increasing the fogginess over their immediate shores. The effect, such as it is, seems to be somewhat greater in the case of the upper Lakes.

The fog observations made at the usually rather widely separated stations of the Weather Bureau can hardly give an accurate picture of the distribution of the more or less local fogs that occur over the interior districts. A detailed map of fog distribution based upon the observations made by thousands of observers, located some in valleys and some on hills, some on lakes and some on dry plains, some in forested areas and some in the desert, would show a very "patchy" distribution, in which topography would be the main control. The facts shown on the accompanying map (Fig. 110), however, give a reasonably accurate broad view, amply sufficient for purposes of a general climatic survey. Over the interior districts of the eastern portion of the country as a whole dense fog is relatively infrequent (less than ten days a year), the central and southern portions of the Appalachian Mountains having the maximum fogginess, which exceeds that of all but two very restricted areas on the Atlantic and Gulf coasts. These large figures for the Appalachian area doubtless represent local valley fogs. Over the arid or semi-arid western interior mountain and plateau districts there is a very large area with dense fog on fewer than five days annually.

Inland Fogs Due to Radiation. The fogs of the United States may be classified in two main groups: *inland* and *marine*.[1] The former may be further subdivided according to their origin. There are the fogs that are due chiefly to local radiation, probably usually combined with a slow air drainage. These are characteristic of clear, calm nights under weak barometric gradients. They are familiar phenomena in valleys, over and near rivers and ponds, and on lowlands as contrasted with

[1] For a general brief discussion of fogs in the United States see A. J. Henry, "Climatology of the United States," *Bull. Q*, pp. 63–64; H. C. Frankenfield, "Fog Forecasting in the United States," *Proc. 2d Pan-Amer. Sci. Congr., Washington, U. S. A., December 27, 1915, to January 8, 1916*, Washington, D. C. (1917), Sect. II, Vol. II, pp. 659–670, and also "Weather Forecasting in the United States," *U. S. Weather Bur. No. 583* (1916), pp. 260–274 (Figs. 172, 173, 175–177 show fog-type weather maps).

neighboring slopes and hilltops. Hence they are generally known as valley and lowland fogs. These fogs are local. They usually begin to form toward or soon after sunset, "burn off" soon after sunrise, although occasionally lasting longer, and are most common and best developed during winter nights. They are, however, by no means limited to that season. Valley and lowland fogs of autumn, as well as, less frequently, of spring and summer, are familiar nocturnal phenomena in hilly or mountainous districts. They are of relatively slight vertical extent, 100 to 200 feet being usual maxima of thickness. Such local radiation fogs occur all over the United States where weather conditions and topography are favorable, but they are least frequent in the more arid portions of the western plateau and mountain districts. In the California valley, fogs of this group are locally known as "tule" fogs because of their common occurrence over the low-lying swamps and bottom lands where Mexican bulrush (tule) grows. During the prevalence of tule fogs the surface flow of air is from the land to the sea, and the fog which has formed over the marshes is carried slowly seaward by this air movement. The California foothills region is mostly above this winter fog belt. Because of their usual occurrence over a comparatively restricted area, radiation fogs, although well and widely known, have not been adequately studied either in a large way or for individual districts. They may, however, be of considerable importance to man, especially in the matter of delays to transportation and the liability of accidents at such times. In a mountainous or a hilly country the houses and villages situated along valley bottoms, on lowlands, or on the lower slopes of the hills are often enveloped in a thick fog during the evenings, nights, and early mornings, while people living at slightly greater elevations, on the adjacent slopes or on the hilltops, are under clear skies at night and enjoy the early morning sunshine.[1]

[1] "Pogonip" is an Indian name locally used in some of the mountainous portions of Nevada for a frozen fog, or "mist of ice crystals" (see *Amer. Met. Journ.*, Vol. 4 (1887–1888), p. 105; *M. W. R.*, Vol. 22 (1894), pp. 76–77, and Vol. 28 (1900), p. 450). The phenomenon is also occasionally observed elsewhere (for example, in Wyoming and in Colorado). According to reports the Indians and many of the white settlers dread the "pogonip," and believe that to breathe it means certain death.

Inland Fogs Due to Cyclonic Conditions. There are also inland fogs that result from the chilling of warm, moist air as it passes over a snow-covered surface on its way northward toward a cyclonic depression drifting slowly eastward across the northern tier of states from the Great Lakes region to the Atlantic Ocean. Under such conditions a spell of thawing weather, very likely accompanied for part of the time by a warm rain, sets in, and the damp southerly air becomes foggy close to the ground. Fogs of this class are necessarily limited to the colder months. They are well known in the more northern sections of the eastern United States, often extending over considerable areas at one time, and may well be given the name of *cyclonic* fogs. They are usually not very dense. Cyclonic fogs also occur occasionally under somewhat different conditions, as when colder ocean air moves onshore or when, after a winter thaw, a cold westerly wind begins to blow on the rear of the passing depression. Both general and local conditions of fog formation vary, and it is not possible to have rules for classification too hard and fast.

Marine Fogs in General. Marine fogs, produced essentially by the mixture of air of different temperatures (doubtless in many cases associated with a certain amount of eddy motion) and by conduction, occur in three general districts: the Pacific coast, the Atlantic and Gulf of Mexico coasts, and the Great Lakes. Fogs of this group are really marine phenomena, but as they often overlap the coasts they must be considered in any discussion of the climatology of the United States.

Pacific Coast Fogs. Because of their frequency, their great latitudinal extent, and their peculiar importance in relation to navigation in a region where violent storms and high winds are rare, the fogs of the Pacific coast have been well studied.[1] A

[1] See A. G. McAdie, "Fog Studies on Mount Tamalpais," *M. W. R.*, Vol. 28 (1900), pp. 283–286, 492–493, and Vol. 29 (1901), pp. 24–25, 61–63, 104–106; idem, "Climatology of California," *U. S. Weather Bur. Bull. L* (1903), pp. 239–249; idem, "Fog and Frost in the San Gabriel Valley," *M. W. R.*, Vol. 38 (1910), pp. 1895–1896; idem, "The Clouds and Fogs of San Francisco," San Francisco, 1912 (note especially view opposite page 56, "How the Fog comes in at San Francisco"): A. H. Palmer, "Fog along the California Coast," *M. W. R.*, Vol. 45 (1917), pp. 496–499; B. M. Varney, "A Fog Phenomenon of San Francisco Bay," ibid., Vol. 48 (1920), pp. 337–338; H. H. Wright, "Fog in Relation to Wind Direction on Mount Tamalpais, California," ibid., Vol. 44 (1916), pp. 342–344.

few years ago the Marine Exchange of the San Francisco Chamber of Commerce was asked what proportion of the shipwrecks along the California coast was due to fog. The answer was, "All of them."[1]

Marine fogs are a distinctive feature along the Pacific seaboard. At times they may extend along the entire coast from Puget Sound to southern California. Chiefly characteristic of the spring and summer months, they also occur in winter, but less frequently then. They have a much greater vertical thickness than the winter inland fogs, perhaps averaging 1500 feet, but rarely exceeding 2000 feet. These fogs, which extend for fifty miles or so offshore, move in from the ocean with a westerly "sea breeze," arriving on the coast about or soon after sunset and disappearing in the early forenoon. They penetrate inland not more than a few miles. A fog that lasts through the whole day is a rarity in southern California.

Local conditions have much to do with the frequency, the duration, and the characteristics of these fogs. San Francisco, for example, is famous for its fog. Owing to the peculiar topography in the vicinity of that city, where the Golden Gate offers a free entrance for the ocean fog, from May to October "with clocklike regularity great banks of fog march in every afternoon and cover the brown hills" (McAdie). During these fogs the lapse rate (that is, rate of change of temperature vertically) is positive. On Mt. Tamalpais, for instance, it is about three times as great as in the "no fog" condition. The excessive diurnal heating of the interior valley during the summer months causes a strong indraft of chilly ocean air from the coast. This wind, which blows with velocities of twenty-five to thirty miles an hour on summer afternoons at the Golden Gate, carries the fog inland, where it is either dissipated or rises. Above the surface wind blowing in from the ocean below, there is an easterly offshore wind. These ocean fogs, with the chilly onshore winds that accompany them, have doubtless contributed not a little to the popularity, as residential cities, of Berkeley, Oakland, and other places to the west of San Francisco Bay, where there is less fog and less

[1] A. H. Palmer, loc. cit., footnote 1, page 308.

chilly wind. When these ocean fogs drift to and over the warmer land they become "high fog" or stratus clouds. At San Diego this "high fog" is known as the "velo" cloud. It is the common cloud of early morning and is much like the low cloud hanging most of the time off the western desert coast of South America.[1] Carpenter speaks of the velo cloud as reaching its perfection over the littoral region of southern California and as being the chief characteristic of the summer in the San Diego Bay district (March–October).[2] The sun usually breaks through this high fog about 10 A.M. on a normal summer day, the sky clearing shortly afterward and remaining clear the rest of the day until about sunset. The velo is less than one thousand feet above the surface and never extends inland more than sixty to seventy miles from the coast. It becomes thinner with increasing distance from the sea.

In the opinion of the local meteorologists the marine fogs of the Pacific coast are chiefly the result of mixture. The warm, moist air moving toward the land from the ocean passes across the cold ocean current close to the shore, mixes with the colder air over that current, and is also itself chilled by conduction. It seems not to be the water vapor in the lowest levels which is condensed, but rather that of the higher levels.

There is an interesting economic aspect of these summer fogs which has attracted some attention.[3] The fogs are most prevalent in the dry season, when for weeks at a time no rain falls in southern California, and herbaceous vegetation dries up. While the fog itself rarely gives any measurable precipitation, it certainly helps somewhat to relieve the excessive aridity. Occasionally as much as 0.05 in. of water has been

[1] R. DeC. Ward, "A Note on the South American Coastal Cloud," *Science*, Vol. 7 (N. S. 1898), pp. 211–212; Isaiah Bowman, "The Andes of Southern Peru" (New York, 1916), pp. 143–145.

[2] F. A. Carpenter, "The Climate and Weather of San Diego, California" (San Diego, 1913), pp. 5–7, with a photograph of the velo cloud over San Diego Bay. Also "Coast and Desert Cloudiness in California," *Southern Cal. Practitioner*, Vol. 36 (1921), pp. 74–78, with a photograph of the velo cloud over Los Angeles and Pasadena.

[3] See Cleveland Abbe, "The Utilization of Fog," *M. W. R.*, Vol. 26 (1898), p. 466, and Vol. 27 (1899), p. 113; W. G. Reed, "Fog as a Source of Water Supply," ibid., Vol. 44 (1916), p. 288.

deposited in one night, and smaller amounts (0.01 in.) are oftener recorded. The famous redwoods of California (*Sequoia sempervirens*) grow on a narrow coastal strip within the fog belt and nowhere extend inland more than thirty miles. Reed notes that on the Berkeley hills during summer fogs small trees drip with moisture and the ground beneath the trees is moist to a considerable depth. Away from the trees, on the other hand, the ground is dry and powdery and the grass is brown. No practical method has yet been devised by means of which any considerable amount of fog particles can be collected and used for the benefit of vegetation.

Atlantic and Gulf Coast Fogs. The Atlantic coast fogs differ from those of the Pacific in their irregularity and less frequent occurrence. The only portion of the Atlantic coast which in any way equals the immediate Pacific coast in fogginess is northern New England. On the basis of over thirty years' observations, Petit Manan, Maine, holds the record for the largest average annual number of days with dense fog on the Atlantic coast. From New England southward there is a decrease in the number of fogs until at Key West a dense fog is a rare occurrence. A glance at any table showing fog frequencies—for example, the observations collected and published by the United States Lighthouse Service—shows how greatly these frequencies vary even within short distances.[1] The location of a station with reference to adjacent land and water areas, the surrounding topography, and the exposure to the wind are important controls of the amount of fog. Thus certain islands like Nantucket, and certain individual stations like Cape May, New Jersey, have a good many more fogs than other places somewhat differently situated.[2] Occasionally, but rarely, it may happen that a belt of fog extends more or less along the whole Atlantic coast from Maine as far as northern Florida. As a rule, however, the fog extends only part way down the coast, perhaps as far as Boston or New York or some-

[1] See summaries of fog observations made at fog signal stations along the Atlantic coast in *M.W.R.*, Vol. 44 (1916), pp. 21–22, and Vol. 45 (1917), p. 499.

[2] F. W. Proctor, "A Study of the Summer Fogs of Buzzards Bay," ibid., Vol. 31 (1903), pp. 467–472.

what farther, and in most cases the fog belt is found only off the coast of Maine. On the New England coast fogs are most frequent in summer, when the temperature-differences between water and land are most marked and when the warm southerly winds blowing over the cold ocean water near shore are well moisture-laden. Farther south the maximum fog frequency as a whole comes in winter and early spring. The frequent dense summer fogs on the New England coast are somewhat of a handicap to this locality as a summer resort. The sea fogs of the Atlantic seaboard, like those of the Pacific coast, not infrequently drift onshore on hot summer days; their lower layers are warmed over the land, the fog particles evaporate, and the fog becomes a high fog, or velo cloud. Later, when the whole layer has become well warmed by the sun, the fog is completely dissipated.

Along the Gulf of Mexico marine fogs are not a significant element of climate except on the northeastern Texas coast. Their season is winter, and they vary considerably in number according to local controls, as is the case on the Atlantic coast. On the basis of several years' record Pensacola has more fog than Tampa, Mobile, or Corpus Christi. Galveston has about twice as many days with dense fog as the three stations last named.

Fogs of the Great Lakes. Henry distinguishes two forms of fog on the Great Lakes.[1] One of these is a dense unbroken sheet or blanket which forms in spring and fall when a cyclonic depression moves slowly over the lake region, bringing moist east and southeast winds over the cool surface of the water. The other is a broken, low-lying form, with occasional patches of greater density separated by clear spaces. This is a summer, fair-weather type and is stated to be probably due to diurnal changes in temperature. The geographical and seasonal distribution of fog is somewhat complicated and varies a good deal on the different Lakes. According to Frankenfield there is not very much difference over the upper Lakes between winter and early summer in the matter of fog; on the lower

[1] A. J. Henry, *Bull. Q*, p. 64. See also R. E. Pollock, "Fog," on back of the *Meteorological Chart of the Great Lakes* (United States Weather Bureau), June, 1911.

Lakes the maximum is in late winter and spring.[1] Over all the Lakes the least foggy season, in general, is late summer.

"Dark Days." May 19, 1780, is recorded in the annals of New England as "The Dark Day" and as "Black Friday." Work stopped; schools were closed; barnyard fowl went to roost; ordinary print could not be read at noon; candles were lighted. Great fear seized the people. The Day of Judgment was by many thought to have arrived. At Hartford, Connecticut, the legislature adjourned at 11 A.M. A famous incident occurred in the Council, which was also in session on that day. A motion to adjourn having been made, Colonel Abraham Davenport of Stamford rose to his feet and said: "I am against the adjournment. Either the Day of Judgment is at hand or it is not. If it is not, there is no cause for adjournment. If it is, I wish to be found in the line of my duty. I wish candles to be brought."[2] Similar dark days, although few or none as striking as that of 1780, have been observed and recorded since the early days of white settlement in the United States. Of another similar day (Sunday, October 21, 1716) it was said that in the houses of worship "no one could recognize another four seats away, nor read a word in a psalm book."[3] A "yellow day" occurred in New England on September 6, 1881, when artificial light was necessary and activities were largely suspended.[4]

Conditions like these are produced by smoke from forest fires and are not uncommon, especially over the northeastern section, during prolonged droughts in spring, summer, or autumn. The general drift of the atmosphere being eastward, smoke from fires in the lake region, and even considerably farther west, may thus be transported far and wide over the eastern United States and off onto the Atlantic. A striking case was that of the extensive forest fires in Idaho in August, 1910. Dark days prevailed over a larger area of the United

[1] H. C. Frankenfield, loc. cit., footnote 1, page 306. See also *Meteorological Charts of the Great Lakes*, published by the United States Weather Bureau from January, 1911, to September, 1913 (on these charts the percentages of days with fog are shown for each lake during the navigation season).

[2] Sidney Perley, "Historic Storms of New England" (Salem, Massachusetts, 1891), pp. 105–114. This incident has been immortalized in Whittier's poem, "The Tent on the Beach." [3] Ibid., pp. 29–30. [4] Ibid., pp. 336–337.

States than had ever before been recorded. The shaded portion of the accompanying map (Fig. 111) shows the area over which artificial light was necessary during the daytime from August 19 to August 25.[1] The smoke itself extended far beyond the shaded area. Often, of course, the forest fires are much nearer at hand. Thus, New England has frequently experienced "dark" or "yellow" days when there were fires in eastern

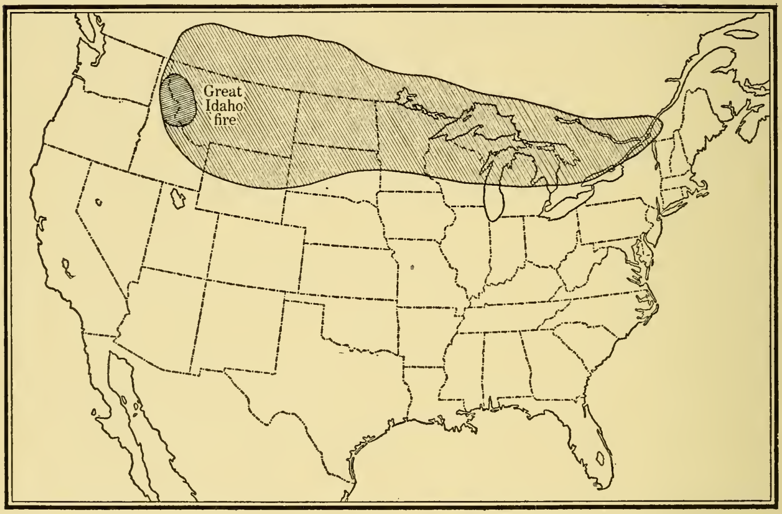

FIG. 111. Area in which Dark Days occurred caused by Smoke from the Great Idaho Fire, August 19–25, 1910

Canada, or in the New England states themselves. Because of its location in the northeastern corner of the country, the fact that the tracks of most of the cyclonic storms which cross any part of the United States converge here, and its considerable remaining forest cover, New England naturally has the largest number of dark days, as is seen in the accompanying chart (Fig. 112).[2] Indeed, many dark days have been practically limited to the New England states.

[1] Fig. 3 in F. G. Plummer, "Forest Fires: their Causes, Extent, and Effects, with a Summary of Recorded Destruction and Loss," *U. S. Dept. of Agric., Forest Service Bull. No. 117*, 1912 (gives a table of dark days in the United States and Canada, 1706–1910; also historical notes). [2] F. G. Plummer, loc. cit., Fig. 2.

The usual drift of the smoke, as has been said, is eastward. When the wind is easterly, however, the smoke drifts west. Thus, some of the smoke from the Idaho fire of 1910 was carried westward onto the Pacific. The British ship *Dunfermline* reported that a smell of smoke was noticed five hundred miles west of San Francisco, and that the haze prevented

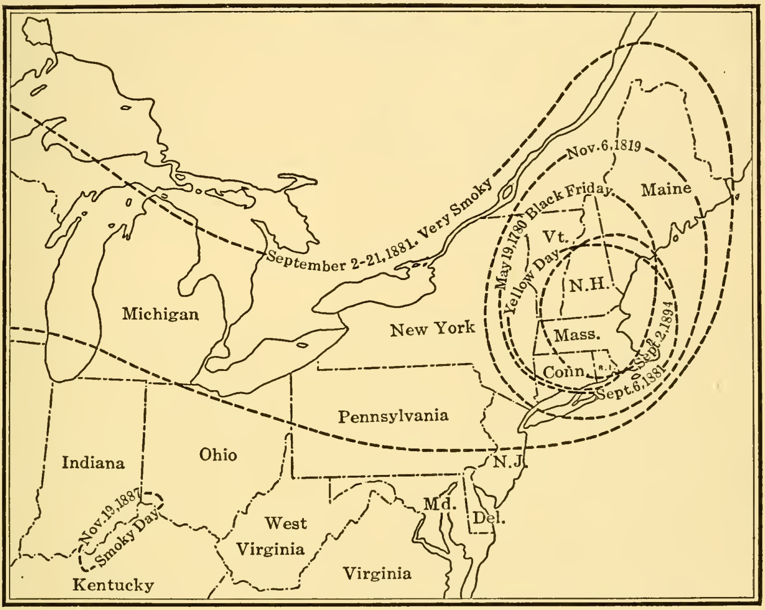

FIG. 112. Area in the Northeastern States in which occurred the Most Important Dark Days since 1780

observations for several days. In October, 1918, smoke from forest fires in western Minnesota was carried by northeasterly winds across North Dakota and later into Nebraska.[1] Again, in the second week of June, 1923, smoke from fires in northern Maine and in New Brunswick was carried by a northeast wind to eastern Massachusetts. The sky was covered with a yellowish-gray sheet, the sun was a dull red, and the day was dark.

[1] Herbert Lyman, "Smoke from Minnesota Forest Fires," *M. W. R.*, Vol. 46 (1918), pp. 506–509 (with charts showing the distribution of the smoke).

On June 12, when the writer was leaving Boston Harbor by steamer, the smoke was so thick that the fog signal at Boston Light was being regularly blown. As the ship drew away from land, the smoke was left behind. When thick smoke drifts over the ocean or over the Great Lakes, it may for a time seriously interfere with navigation. Such conditions have not infrequently occurred on the northern Pacific coast, especially in the Puget Sound region, as well as along the Atlantic coast. When an ordinary marine fog happens to combine with the smoke from a forest fire, or even with that from a neighboring city, the darkness and turbidity of the air are greatly increased, and navigation may come to a complete standstill.

CHAPTER XIV

THUNDERSTORMS

THUNDERSTORMS AS CLIMATIC PHENOMENA · WEATHER CHANGES DURING A TYPICAL SUMMER THUNDERSTORM · THE LARGER CHARACTERISTICS AND HABITS OF AMERICAN THUNDERSTORMS · DISTRIBUTION OF THUNDERSTORMS IN PLACE · DISTRIBUTION OF THUNDERSTORMS IN TIME · THUNDERSTORM WEATHER TYPES · THUNDERSTORMS IN RELATION TO MAN: RAIN, WIND, AND HAIL · LIGHTNING DANGER, DAMAGE, AND PROTECTION

Thunderstorms as Climatic Phenomena. As essential characteristics of American climates, thunderstorms have a broad human interest. From the viewpoint of climatology the distribution of thunderstorms is of more interest than their mechanism. The part played by their rains in watering crops is of greater importance than the size of their raindrops. The damage done by their lightning and hail is of more concern than the cause of the lightning flash or than the origin of the hailstones.

Weather Changes during a Typical Summer Thunderstorm. Individual observers have little conception of the extent and general character of a thunderstorm. They can see neither through the cloud up to its top nor to any distance across its falling rain. Of its height and of its extent they can thus have little information. Yet everyone observes thunderstorms, usually with considerable care, because they are phenomena which attract attention. They are always impressive, often violent, occasionally dangerous.

The self-recording instruments at Blue Hill Observatory, Readville, Massachusetts, kept an accurate account of the changes in temperature, humidity, and pressure, and of the amount of rainfall, during the passage of a typical thunder-

storm on August 12, 1886.[1] The curves in Fig. 113 illustrate weather conditions and changes which are perfectly familiar, but the physiological and economic relations of which are

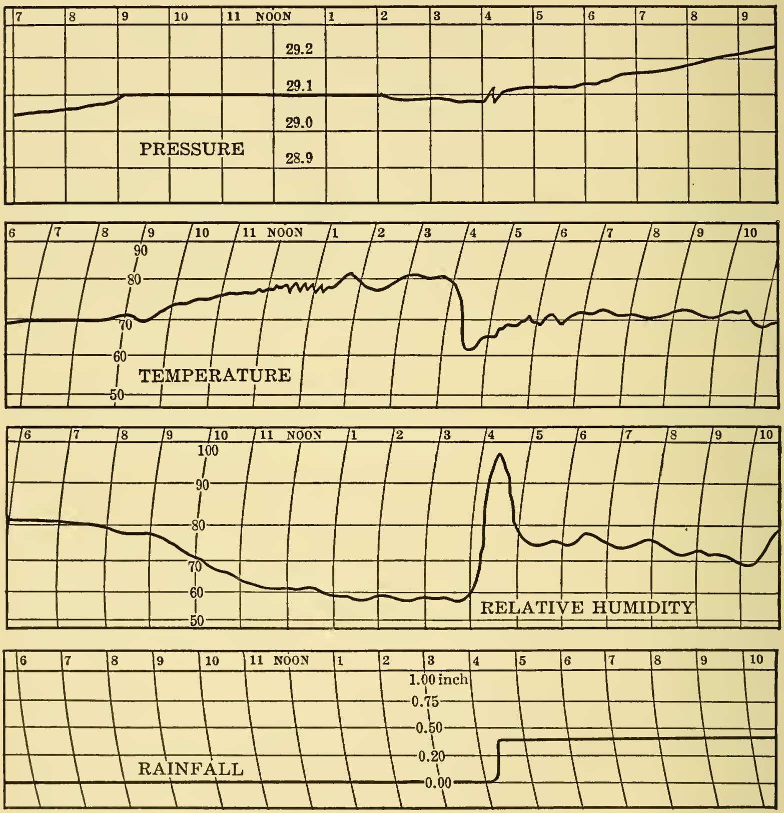

FIG. 113. Meteorological Records obtained during the Passage of a Summer Thunderstorm at Blue Hill Observatory, Massachusetts

perhaps not fully appreciated. A thunderstorm day is usually close, muggy, and oppressive, with temperatures of 80°, 85°,

[1] R. DeC. Ward, "Thunderstorms in New England during the Years 1886 and 1887" (Investigations of the New England Meteorological Society for the Year 1891), *Annals Astron. Obs. Harv. Coll.*, Vol. 31, Part II (1893), pp. 261–343, Plates VII–X. Plate VIII is here reproduced as Fig. 113; Plate IX, Figs. 12 and 15, as Figs. 118 and 119, and Plate VII, Fig. 4, as Fig. 122.

90°, or even higher. Reports of sunstrokes and of prostrations by the heat come from the congested cities, for thunderstorm weather is good sunstroke weather. The advancing clouds serve as a shield against the hot sun, and the temperature begins to fall, but not enough at first to bring any decided relief. For a few minutes, perhaps, the wind shifts and blows toward the approaching storm, a fact which has given rise to the proverb, "A thunderstorm comes up against the wind." Then, suddenly, a short, sharp squall rushes out just in front of the downpouring rain. Advancing with a rolling motion at its forward edge, this thundersquall raises clouds of dust from dry country roads and from city streets. It quickly makes "white caps" on lakes, ponds, or rivers. Its coming is a warning that the rain is close at hand. The pressure suddenly rises as the squall passes over the barometer, and causes the characteristic thunderstorm "nose" on the pressure curve. This change in pressure has much interest to those who are concerned with the mechanics of thunderstorms. For a few minutes only does the squall blow, but it brings a rapidly falling temperature — a most welcome relief after the oppressive heat of the preceding hours. The mercury falls 5°, 10°, 15°, even 20°, in a short time, under the combined influence of the cold rain, the shade, and the active evaporation. Then comes the rain, first in a few large drops, later in the characteristic thunderstorm downpour, clearing the hazy air and refreshing the hot and dusty earth. A half-inch, an inch, perhaps even more, falls in half an hour or so. If the sun has not set, a rainbow may be seen on the rear of the disappearing storm — "a rainbow at night," which is "the sailor's delight," for the storm has passed by. The rumbling of the thunder becomes fainter and fainter in the distance. A cool and refreshing evening and night follow.

The Larger Characteristics and Habits of American Thunderstorms. The thunderstorms of the eastern United States are characteristic American phenomena. In size, in intensity, and in frequency of occurrence they are unique. Hundreds of observers, carefully noting the times of occurrence of various critical phenomena, have furnished the data which have made

it possible to trace the life history of many of these storms. Their position at successive half-hour, hour, or longer intervals has been plotted. Thus, and not by individual observations at a single station, is it possible to gain an understanding of the real nature of these phenomena.

The best way to become familiar with the larger facts concerning thunderstorms and their movements is to examine the accompanying charts (Figs. 114–120). These tell their own story. The numbered lines show the successive positions of the storm front at different hours. Fig. 114 shows the first thunderstorm ever charted for the United States. This storm occurred on July 31, 1877, and moved across Iowa between 6 A.M. and 6 P.M., the storm front becoming wider as it advanced.[1]

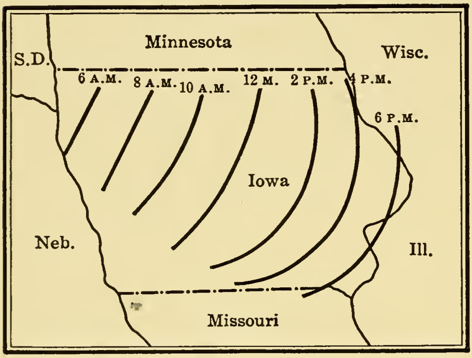

FIG. 114. Thunderstorm in Iowa, July 31, 1877

Fig. 115 is the map of a thunderstorm system of great extent, observed May 18–19, 1884.[2] The broken curved lines show the storm front at successive four-hour intervals on May 18; the solid lines refer to May 19. It will be noticed that the district of storm activity moved to the eastward between May 18 and 19, and that at 4 P.M., May 19, the storm front extended from northern New York to Alabama.

Fig. 116 is a thunderstorm distinguished by a marked squall wind, charted by H. H. Clayton (July 5, 1884).[3] It began in northeastern Missouri about noon and moved southeastward,

[1] W. M. Davis, "Elementary Meteorology" (1894), Fig. 90.

[2] H. A. Hazen, "Thunderstorms of May, 1884," *U. S. Signal Service Notes*, No. XX, 1885. Charts A, B. The Signal Service undertook an investigation of thunderstorms during the summer of 1884 over the area between the 102d meridian and the Atlantic Ocean, and from latitude 35° N. to the northern boundary.

[3] H. H. Clayton, "The Thundersqualls of July 5" (1884), *Amer. Met. Journ.*, Vol. 1 (1884–1885), pp. 263–272, Fig. 2.

with a convex front, at the rate of somewhat over fifty miles an hour, dying out not far from the Atlantic coast about midnight.

Fig. 117 illustrates a New England thunderstorm, July 21, 1885, charted by W. M. Davis.[1] This came "ready-made" from the West. Three separate and distinct storms, of small extent, which occurred partly simultaneously in New England

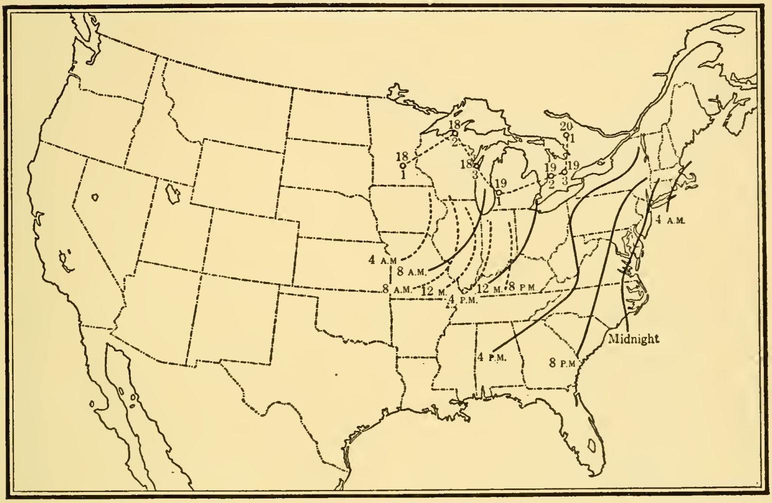

FIG. 115. Thunderstorms of May 18 and 19, 1884

on June 26, 1886, are shown in Fig. 118, and one New England storm of July 29, 1886, is shown in Fig. 119. These storms were charted by R. DeC. Ward.

The thunderstorms of June 7, 1892, are the last general ones which have been charted for the United States (Fig. 120).[2] On

[1] W. M. Davis, "Thunderstorms in New England in the Summer of 1885," *Proc. Amer. Acad. Arts and Sci.* (Boston, Mass.), Vol. 22 (July, 1886), pp. 14–58, Figs. 1–8. (The work of the New England Meteorological Society in 1885–1887 gave more detailed information concerning the thunderstorms of New England than is available for any other part of the United States. The investigation was carried out with assistance from the United States Signal Service and from the Bache Fund of the National Academy of Sciences. Between three hundred and five hundred volunteer observers coöperated.)

[2] N. B. Conger, in "Report on the Forecasting of Thunderstorms during the Summer of 1892," *U. S. Weather Bur. Bull. 9*, 1893 (includes papers by R. DeC. Ward for New England and by Charles M. Strong for Ohio. A study undertaken

that day a belt of thunderstorm activity which had been noted in Wisconsin and Illinois the day before moved east across eastern Indiana, Michigan, and Ohio.

The larger thunderstorms occur within certain well-defined areas or zones. These zones of thunderstorm activity move eastward across country. Thus, on successive days states farther and farther to the east have their thunderstorms under conditions similar to those which previously prevailed to the west. Borne along by the upper currents at the levels of the thunder-clouds, the thunderstorms themselves also move eastward, spreading out as they go. The area which a single storm covers is therefore usually roughly fan-shaped, the handle of the fan being toward the west. They travel with the speed of a moderately fast train (thirty to forty miles an hour). Sometimes they rush ahead as fast as an express train (fifty or more miles an hour). Sometimes they move no faster than a horse can trot, or occasionally even come to a dead stop for a short time. Knowing the rate of progression and the duration of the rain at any place, it is a simple matter to determine the width of the area over which rain is falling at one time. If the storm moves at forty miles

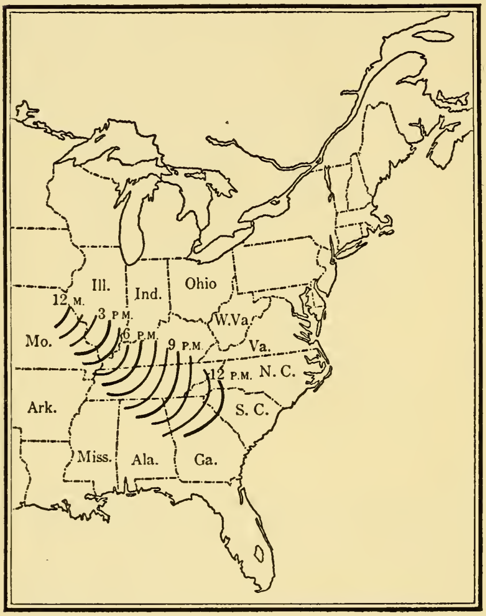

FIG. 116. Thunderstorm of July 5, 1884

by the Weather Bureau in 1892 with special reference to an improvement in thunderstorm forecasts. The area embraced in this investigation extended from the upper Mississippi east to the Atlantic coast).

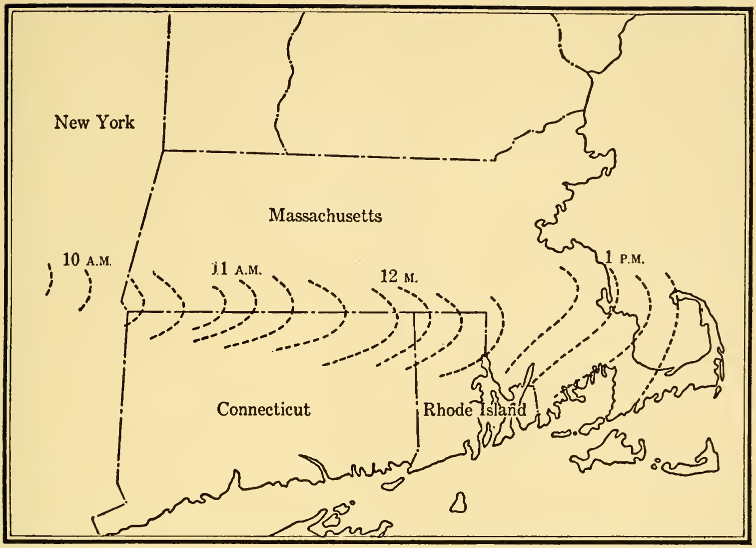

FIG. 117. Thunderstorm of July 21, 1885, in New England

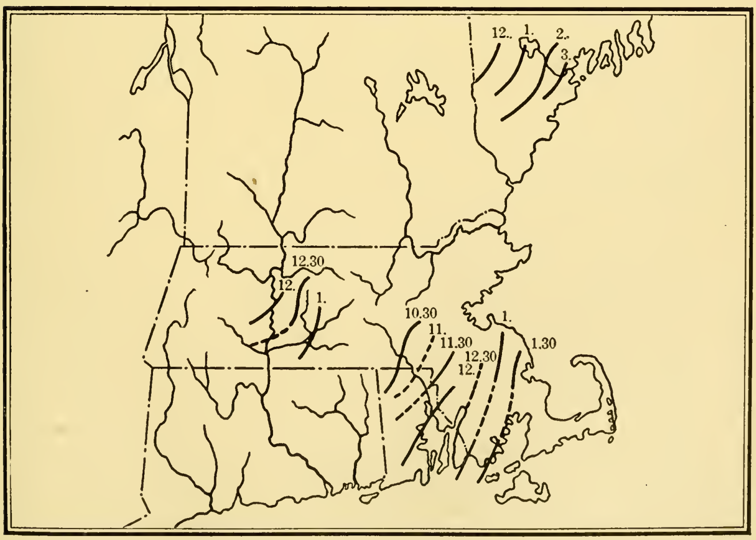

FIG. 118. Thunderstorms of June 26, 1886, in New England

an hour and the rain lasts half an hour, the width of the rain belt is about twenty miles. Its length corresponds to the length of the storm front. This area is generally roughly lens-shaped, convex to the east and concave to the west.

Thunderstorms are not all alike. There are some which are almost tornadic in their violence, last for hours, and cross several states, covering a distance as great as that from the Mississippi Valley to the Atlantic. There are some so small and so mild that they are limited to a county or two in a single state, and bring but a few peals of thunder in a gentle shower of rain.

Distribution of Thunderstorms in Place.[1] Fig. 121 shows the essential facts concerning the distribution of thunderstorms.

[1] See section on Precipitation and Humidity of the *Atlas of American Agriculture*, text page 44, Fig. 81 (here reproduced as Fig. 121); W. H. Alexander, "Distribution of Thunderstorms in the United States," *M. W. R.*, Vol. 43 (1915), pp. 322–340 (with charts showing the monthly and annual numbers of thunderstorms for ten years, 1904–1913, inclusive); "Percentage Frequency of Thunderstorms in the United States, 1904–1913," ibid., pp. 619–620 (a summary, in percentages and by months, of the data used by W. H. Alexander in his discussion of the distribution of thunderstorms above referred to); W. H. Alexander, "Thunderstorms," *Proc. 2d Pan-Amer. Sci. Congr., December 27, 1915, to January 8, 1916*, Vol. II, Sect. II: Astronomy, Meteorology, and Seismology, pp. 55–75 (gives chart showing distribution of thunderstorms for 1904–1913; curves showing relation of monthly rainfalls to the total numbers of thunderstorms at Cleveland, St. Louis, Tampa, and Santa Fé for each year from 1904 to 1913; also a bibliography). The following general references may also be found useful: "Bibliography of Meteorology. A Classed Catalogue of the Printed Literature of Meteorology from the Origin of Printing to the Close of 1881; with a Supplement to the Close of 1889, and an Author Index." Prepared under the direction of Brigadier General A. W. Greely, Chief Signal Officer, U. S. A. Edited by Oliver L. Fassig, 1891. Part IV: Storms (pp. 292–296 on thunderstorms and squalls in the United States); M. W. Harrington, "Rainfall and Snow of the United States, compiled to the End of 1891, with Annual, Seasonal, Monthly, and Other Charts," *U. S. Weather Bur. Bull. C*, 1894, Atlas and Text (Chart XXIII gives details of occurrence of thunderstorms: average annual number, months of maximum number, percentages of winter thunderstorms, and directions of thunderstorms other than west; text pages 29–30); A. J. Henry, "Climatology of the United States," *U. S. Weather Bur. Bull. Q*, 1906 (pp. 75–76 on thunderstorms; Plate XXVIII gives the average annual number of thunderstorm days in the United States); W. J. Humphreys, "The Thunderstorm and its Phenomena," *M. W. R.*, Vol. 42 (1914), pp. 348–380 (includes several thunderstorm weather maps); "Weather Forecasting in the United States," *U. S. Weather Bur. No. 583* (1916), pp. 274–278, 310–311; Figs. 178–185. W. H. Alexander has prepared a revision of the data given in his earlier paper (1915), using a twenty-year period (1904–1923) and including monthly and annual charts of thunderstorm distribution ("The Distribution of Thunderstorms in the United States," ibid., Vol. 52 (1924), pp. 337–343). The results of the two investigations are in close agreement in all important details.

The data must not be taken too literally. Considerable diversity among observers as to what constitutes a thunderstorm day is inevitable. No part of the country is entirely free from thunderstorms. The center of greatest frequency is along the eastern and central Gulf coast (over ninety days a year). A secondary center is in northern New Mexico. It is noticeable that these two regions differ markedly from one another in

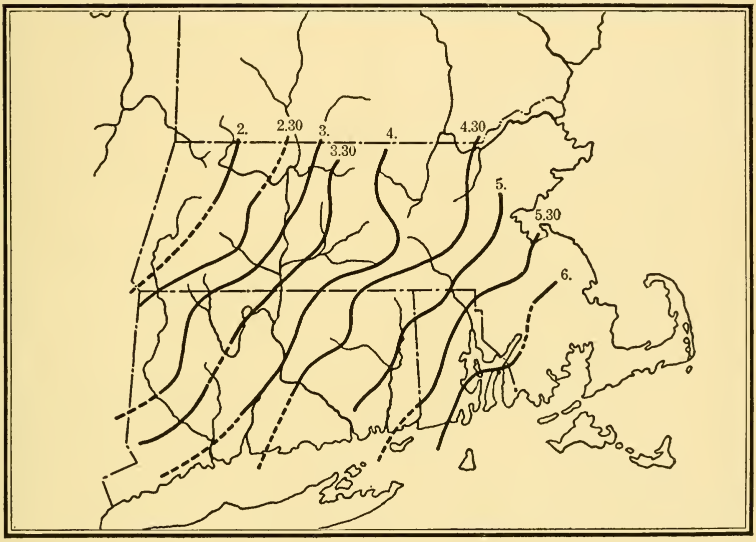

FIG. 119. Thunderstorm of July 29, 1886, in New England

altitude as well as in climate. In both cases the thunderstorms are chiefly local phenomena. Topography is seen to have an important control over the occurrence of thunderstorms. The northern tier of states has distinctly fewer thunderstorms than the southern. It is over the immense area east of the Rocky Mountains that the great state-wide thunderstorms occur whose characteristics have been described. Throughout this area, also, on hot summer afternoons, many scattering sporadic thunderstorms spring up, of local importance because they supply rain, but not combined into any general system or group. These local storms are more frequent in southern

sections, especially in the Gulf states, and during the warmer months may occur in spells day after day with almost tropical regularity.

It is a characteristic of arid and semi-arid regions that thunderstorm rains often do not reach the ground, but evaporate on the way from cloud to earth. With exasperating frequency the farmers of the Great Plains watch the building up of immense thunderstorm clouds on hot summer afternoons and see the gradual preparation for the production of a heavy and much-needed rain, only to be disappointed by the failure of the shower to survive until it falls to the surface. Similarly, many thunderstorms form over the higher mountains of the western Plateau states and drift off over the lowlands to the east. Their rain completely evaporates before it can reach the parched and dusty ground, or perhaps they give only a disappointing sprinkle instead of the heavy shower which has been seen falling on the distant mountain slopes, and which temporarily replenished the mountain streams.

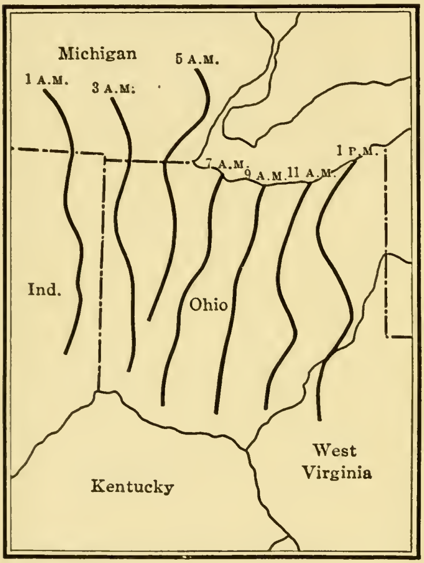

FIG. 120. Thunderstorms of June 7, 1892

The thunderstorms of the mountains and plateaus of the West are chiefly local, short-lived, and sporadic. They find their opportunity in the warm air ascending the mountain sides or rising from the broad plateaus. They supply much of the heavier rainfall of the higher elevations. Most of them are born and die unnoticed and unrecorded on far-away uninhabited slopes, or in deep rocky cañons remote from human settlements. Occasionally there comes a sudden downpour over a limited area of arid mountain country — a cloud-burst, so

called—which in a few minutes changes dry river beds in deep cañons into raging torrents, sweeping away hunters, prospectors, farmers, cattle, everything within reach of the seething waters. Strongly contrasted with such heavy downpours are the great clouds of dust produced by the squall winds of thunderstorms which advance across the Western plains and deserts without bringing any rain. These are often

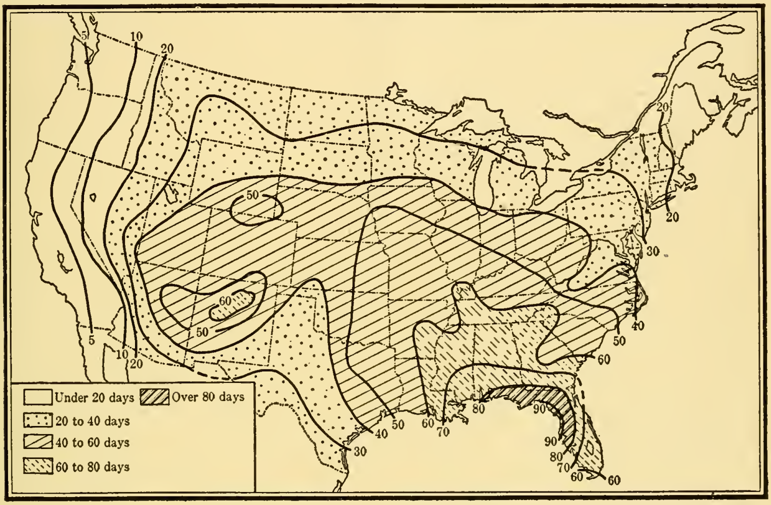

FIG. 121. Average Annual Number of Days with Thunderstorms

real dust storms. Occasionally electric storms, without clouds or precipitation but often accompanied by dry and dusty winds, are observed in fine weather on the Western plains, in the foothills, or at the higher altitudes on the Western mountains. The air is highly electrified. Light electrical discharges may be seen in the air or may take place through the body. Wire fences and other metallic objects give shocks when touched. Mountain tops, trees, the horns of cattle, and other objects are sometimes tipped with "balls of fire."

On the Pacific slope lowlands thunderstorms are comparatively infrequent and usually light. They are not often experienced on the immediate coast, the available data indicating

that they are there recorded on from two to four days a year. In the interior valleys and on the mountains they occur much more frequently. They are characteristic summer phenomena on the higher mountain slopes and furnish much or all of the "dry season" rainfall of those localities. Summer convectional thunderstorms in the mountains and deserts of southern California (Sonoras), accompanied by Sonora clouds, frequently give very heavy local rainfalls of the cloud-burst type, washing away railroads, roads, and bridges.[1] Lightning from these storms often sets forest fires.

Thunderstorms of past years ("fossil thunderstorms") may often be detected by the damage done by their squall winds in uprooting and breaking off trees in forests and by the "fulgurites" of vitrified sand caused by lightning flashes which struck into the earth.

Distribution of Thunderstorms in Time. In relation to man's activities it is of significance that most thunderstorms occur at the time of year and at hours when outdoor activities are at their height; that is, in the warmer months and the warm hours of middle or late afternoon. Whatever benefit or injury they may bring therefore forces itself upon public attention. These are the times when farmers are likely to be at work in their fields and when those who enjoy summer vacations are making the most of their outdoor life. Hence picnics and all kinds of summer excursions, to say nothing of the more serious business of the agriculturist, are often interfered with. Yet thunderstorms may come at any time, day or night. People are often awakened from a sound sleep by the heavy rainfall, the lightning, and the thunder of a late night storm or an early morning storm. Except for the annoyance of being awakened, and the possible fear of lightning danger, these night storms do not immediately affect man's comfort or his plans. Night thunderstorms seem to be less frequent in the Gulf Province and in the Southern states generally than elsewhere in the East. Along the Atlantic coast the comparatively rare thunderstorms of winter prefer the evening and night

[1] Dean Blake, "Sonora Storms," *M. W. R.*, Vol. 51 (1923), pp. 585–588 (gives references; also a type map for the occurrence of Sonora storms).

hours, and are generally associated with the wind-shift line of well-developed cyclonic storms.

The season of thunderstorms varies more or less according to latitude. The Southern states may be said to be in the thunderstorm belt throughout the year. In the Gulf Province thunderstorms, or general rains accompanied by thunder, are not uncommon in winter, occurring with decreasing frequency northward. In winter the center of maximum thunderstorm activity is over the middle Gulf states. This center moves northward as spring and summer come on, advancing both north and west. By July the centers of maximum activity are in Florida and in New Mexico. Taking the country as a whole, January brings the fewest thunderstorms and July and August the most. Late spring and early summer bring considerable thunderstorm rainfall, which is of marked economic importance over the eastern Rocky Mountain foothills and the Great Plains. Over the Plateau region the thunderstorms of late summer are the most frequent. In New Mexico and Arizona these bring the well-marked summer rainy season of those states (July–August).

On the Pacific slope, while the inland thunderstorms show a preference for summer, the rarer ones of the immediate coast develop chiefly in winter.

Thunderstorm Weather Types. The thunderstorms of the eastern United States are not uniformly distributed through all types of summer weather. They come, numerous, widely extended, well marked, during a few days, and then there is a lull. Perhaps two or three or more days of cooler, clearer weather pass by with but a few scattering ones, or none at all. This more or less clearly defined periodicity is related to the larger movements of the atmosphere and may often be taken advantage of in planning outdoor work or sport. Thunderstorms depend upon temperatures below and aloft. They may result (1) from the excessive heating of the lower air ("heat thunderstorms") or (2) from the arrangement of the lower and upper currents under the control of a passing cyclonic storm area ("cyclonic thunderstorms") or (3) from a combination of both causes. From the viewpoint of climate interest centers

in the weather conditions on the earth's surface which are associated with thunderstorm occurrence, and which immediately affect human beings, and not on what occurs overhead in the cloud levels.

The preponderance of thunderstorms in the afternoon hours shows that the warming of the lower air by the sun during the day plays an important part in thunderstorm development, whatever may be the special relations of the air currents below and aloft. But most thunderstorms occur in a fairly definite position with relation to a center of low pressure. Hence the name "cyclonic thunderstorms." In Fig. 115 the dotted lines at the top show the positions and path of the cyclonic center in connection with which the thunderstorms of May 18 and 19, 1884, occurred. As this center moved east, the district of thunderstorm activity moved east also. For New England, Ward has drawn lines joining the thunderstorm district with the contemporaneous center of low pressure nearest New England. The results for August, 1886, are shown in Fig. 122.

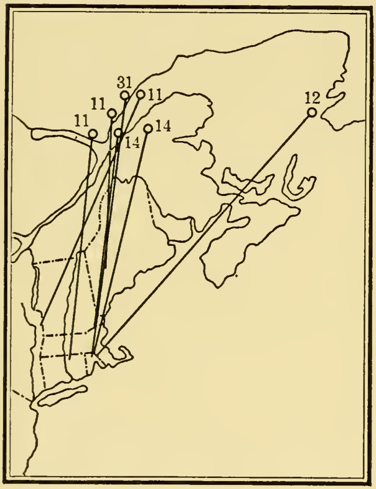

FIG. 122. Relation of Thunderstorms to Cyclonic Centers in New England, August, 1886

Most of the largest and best-developed thunderstorms of the eastern United States occur in or close to the transition zone between the warm, muggy weather brought by the southerly winds in front of a passing cyclonic area, and the cooler, drier, clear weather which comes with the westerly and northwesterly winds in its rear. The ideal conditions for this type are attained when the contrasted southerly and westerly winds are in the most marked opposition. This happens when the southern portion of the low pressure area is a trough, or V-shaped,

making what is known as a "wind-shift line." Along this wind-shift line there often develops a long row of thunderstorms ("line thunderstorms") progressing eastward as a body with the advance of the trough itself. Thunderstorms of this type often come as a welcome relief at the close of an enervating and depressing hot spell. They are usually followed by two or three days of bright, clear, cool weather—the summer cool wave, refreshing, invigorating, health-giving. Thunderstorms of this type occur in winter over the southern Atlantic coast states, occasionally reaching as far north as New England. The proverb current in parts of the South that "a thunderstorm in winter means colder weather" refers to the fall in temperature brought by the northwesterly winds as the wind-shift line passes.

Thunderstorms also spring up in the hot, muggy southerly winds in advance of the low pressure center; others, less frequently, develop in the zone of cool northwesterly or westerly winds on its rear. The former, while accompanied by a temporary lowering of temperature, are not likely to be followed by a cool day, since the warm southerly winds in which they occur usually continue for some hours before the cooler westerly winds arrive. Thunderstorms of the second class come on generally fine days, cooler and more comfortable than those associated with "hot spells." These also are not followed by a marked fall in temperature, for they are themselves in the cool quadrant of the cyclone. The northwesterly winter snow squalls are probably essentially of the same nature.

Fig. 123 is a broadly generalized composite map showing conditions under which cyclonic thunderstorms are likely to occur over the area from the central Mississippi Valley eastward. As the low pressure area moves east or northeast, the thunderstorm district moves with it. The latitudes over which such cyclonic thunderstorms will occur naturally depend upon the position, movement, and characteristics of the cyclones. Cyclonic thunderstorms develop under other conditions in relation to their parent cyclone than those just described. In the upper Missouri valley and on the northeastern Rocky Mountain slopes, as noted by Henry, they are frequent in the

northwest quadrant. Again, while ordinary widespread rainstorms are unfavorable to thunderstorm development, there are many occurrences of lightning and thunder during such general rains. The characteristic features of these nondescript thunderstorms are usually merged in those of the larger storm. Sometimes a line thunderstorm at the end of a prolonged general rain results in a definite clearing. Favorable thunderstorm

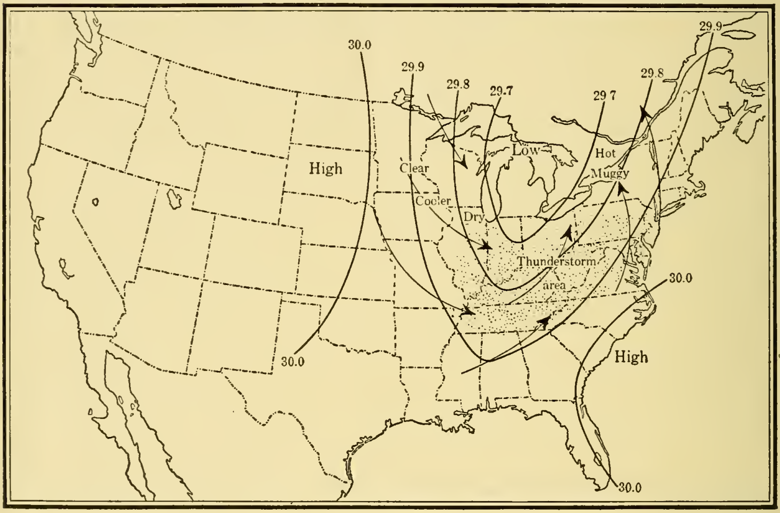

FIG. 123. Cyclonic Thunderstorm Type Map

conditions are occasionally found where temperatures are sharply contrasted along the boundary line between warmer and cooler winds; for example, on the New England coast, where a cool easterly wind from the ocean pushes its way into a general flow of warm southerly winds over the land.

On the Pacific slope the winter thunderstorms of the California coast move in from the ocean in connection with general cyclonic conditions. Farther north, in Oregon and Washington, the summer thunderstorms are usually associated with a low pressure area originating in the heated valleys of central and northern California. The low moves northward into eastern Oregon, eastern Washington, or Idaho, increasing in develop-

ment and in area covered. High pressures prevail over northwestern Washington, and thunderstorms occur on the western or northwestern quadrants of the low.

There is no hard-and-fast line between cyclonic and heat thunderstorms. Heat thunderstorms, so called, are those which spring up locally, on hot, muggy, relatively calm summer afternoons, when there is a generally uniform, rather nondescript pressure distribution, near or but slightly below normal, over a wide area. They often develop at many widely scattered places on the same day, sometimes over much of the region east of the Mississippi River, and especially in and near mountains. They usually maintain their own identity without uniting with their fellows; are small affairs, moving but short distances; do not last through the night, but perhaps develop again, day after day, throughout a favorable spell of weather. Heat thunderstorms of this kind are really nothing but overgrown summer-daytime clouds (cumulus). They are usually not followed by cooler weather. While they are far from uncommon over the central and northern portions of the United States east of the Rocky Mountains, they are chiefly characteristic of the Gulf and south Atlantic coast states and of the mountain and plateau districts of the Plateau and Pacific provinces. The summer thunderstorms of California are characteristically heat thunderstorms. It is to this group, therefore, that most of the typical summer thunderstorms of the West belong, which, over some sections, may occur almost daily throughout their season.

Fig. 124 is a generalized map showing conditions favorable for the development of heat thunderstorms over the eastern United States. Many other types of isobaric arrangement might equally well be shown as characteristic of heat-thunderstorm occurrence.

Thunderstorms in Relation to Man: Rain, Wind, and Hail. Thunderstorms bring much that is of benefit. They also cause loss of life and of property. The good and the bad are balanced against one another. To them much, in parts of the country even most, of the spring and summer rainfall is due. Thunderless rains are exceptional in those seasons over extended areas, especially in the western mountain and plateau region. One

good thundershower over a considerable area at a critical crop stage is worth hundreds of thousands of dollars to American farmers. The stock markets time and again show the favorable reaction of such conditions upon the prices of cereals and also of railroad and other stocks. Thundershowers break summer droughts, cleanse the dusty air, refresh the parched earth, replenish failing streams and brooks, and usually bring cool evenings and nights after sultry and oppressive summer days.

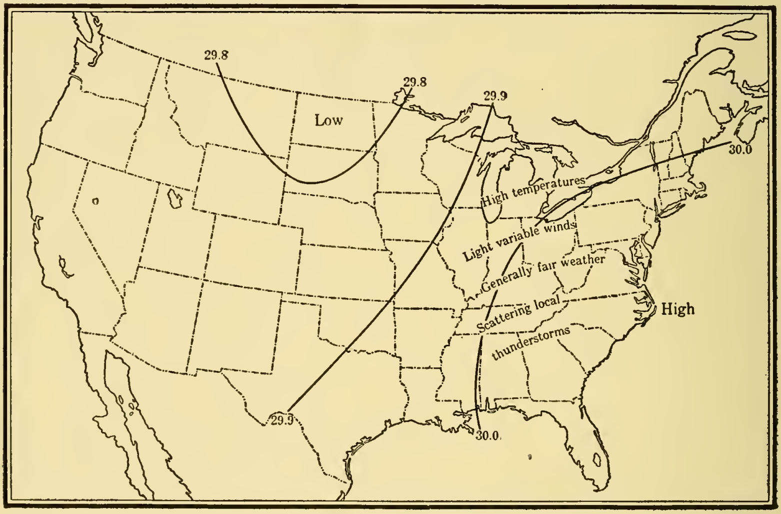

FIG. 124. Heat Thunderstorm Type Map

It is of considerable human and economic importance that the larger thunderstorms are not everywhere equally severe. They are not a well-united whole, but rather a series of storms loosely connected, moving as a body. Thus their action is uneven, their intensity varies, and their destructive effects are usually limited to relatively narrow belts. This fact of varying intensity along the storm front probably partly explains the popular belief that thunderstorms often divide. A careful charting of all New England thunderstorms in 1886 and 1887 failed to confirm the belief that there is any dividing in any special localities. Only very rarely do breaks in the storm front

keep their position in the mass of the moving storm and travel some distance with it. There is another popular belief that thunderstorm movements are controlled by topography. It is true that the smaller, more local storms are influenced, both in their origin and in their movements, by topography, especially by mountains; but it is difficult to believe that the larger thunderstorms, whose mechanism is chiefly at work in the clouds and which move under the control of the higher air currents, can be appreciably affected by hills and valleys.

Turning to the unfavorable aspects, severe thunderstorms often seriously damage and prostrate crops, wet them after harvesting and before they are under cover, flood streets and cellars, and cause local washouts. Most of the heaviest short downpours come in thunderstorms, except in the coast districts which are visited by West Indian hurricanes. The thunder-squall is a phenomenon of no slight importance. Dangerous this squall often is, and sometimes fatal to human life, for it readily capsizes small sailboats and canoes. Its sudden coming should be carefully guarded against. It is often sufficiently violent to snap off branches, to beat down standing crops, and, more rarely, to uproot trees and to wreck buildings.

All severe thunderstorms are occasionally accompanied by hail. Fortunately, however, hail falls over narrow belts in the general storm mass, so that the damage is confined to relatively small areas. When the hailstones are large, windows are broken, crops ruined, and small animals and birds are killed. Cases are reported of the breaking of great numbers of wild birds' eggs by hail, and of the appearance of a smaller number of young birds later in the season. After a severe storm, hail occasionally lies in drifts in the hollows of roads and fields and may even be gathered in considerable quantities. Thus, in New England, July 19, 1886, a woman was reported to have collected a quantity of hailstones by means of which she "made several quarts of very nice ice cream and kindly distributed it among her neighbors." Hail insurance is a natural development in man's relation to this hostile weather element. The increasing use of glass hothouses for raising flowers and garden truck near large cities is a good example of man's desire to make himself more

and more independent of unfavorable climatic conditions. A hothouse is useful for keeping out cold and high winds and damaging rains. It enables man to give his flowers and vegetables a favorable and highly artificial climate under his own control. But the glass cannot stand the heaviest hailstones, and the loss at such times is often very considerable. In some cases greenhouse glass is shielded with wire netting.

In view of its economic importance, increasing attention is being given to the study of the occurrence and geographical distribution of hail.[1]

Fig. 125 shows the average annual number of days with hail during the frostless season, which is the time when hail is of the greatest economic significance because of the likelihood of its injuring growing crops. Obviously the length of this growing season is not the same in all parts of the country. The maximum frequency of hail during the frostless season is seen to occur over the Plains and the Rocky Mountain region. It is rare along the immediate Atlantic, Gulf, and Pacific coasts, over all of southern California, and parts of the southwestern interior. Hail is distinctly less frequent east of the Mississippi River than west of it.[2]

Hail is a warm-season phenomenon. An exception is the immediate Pacific coast from San Francisco northward, where it occurs chiefly from November to March. As a general rule

[1] A. De Riemer and C. Abbe, "The Average Frequency of Days of Hail during 1893–1897," *M. W. R.*, Vol. 26 (1898), pp. 546–547 (an early study, necessarily based on incomplete data); A. J. Henry, "Hail in the United States," ibid., Vol. 45 (1917), pp. 94–99 (with five charts showing the average numbers of days with hail by seasons and for the year); Precipitation and Humidity section of *Atlas of American Agriculture*, text page 44, Fig. 80 (here reproduced as Fig. 125; shows the average number of days with hail during the frostless season for the period 1895–1914).

[2] A. J. Henry's charts of the annual and seasonal numbers of days with hail are based on the period 1906–1915. The chart of annual hail frequency shows that the region of most frequent occurrence (four or more storms a year) is in southeastern Wyoming and eastward therefrom, including the western portions of Kansas, Nebraska, and Oklahoma. Adjoining this region, especially to the eastward, the average number of storms per annum decreases to three over practically all of South Dakota, Nebraska, Kansas, the western and central portions of Iowa, the northwestern third of Missouri, all of Colorado, and the southeastern portion of Wyoming. East of the Mississippi the annual average is two storms a year. A second region of hail frequency is found in southwestern Montana, in southern Idaho, and in the mountain districts of New Mexico and northern Arizona.

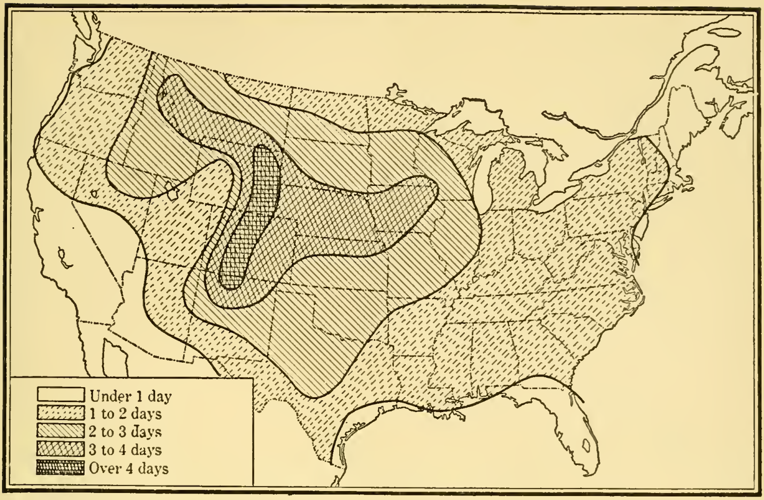

FIG. 125. Average Annual Number of Days with Hail during the Frostless Season

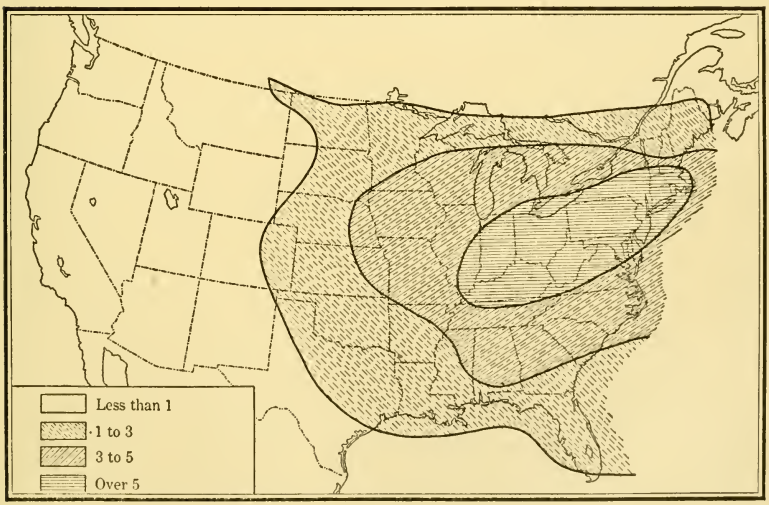

FIG. 126. Geographic Distribution of Deaths by Lightning

Average number per unit area of 10,000 square miles

it is associated with the spring and early summer in the South and with spring and summer in the North. Practically no damage to agricultural crops by hail occurs in the Pacific coast states, and only small damage in the Gulf states, because of the infrequency of the phenomenon and the absence of crops at the time of its most common occurrence.

Lightning Danger, Damage, and Protection. Lightning is powerful and dangerous. Few people care to be exposed to it. Yet there is much needless fear. Most thunderstorms are harmless. Many lightning flashes are too weak to cause death. Large numbers of flashes are from cloud to cloud and are wholly innocuous. Henry has constructed a map showing the average number of fatal cases of lightning stroke annually per unit area of ten thousand square miles.[1] Between seven hundred and eight hundred persons are killed each year, on the average, and probably fully twice as many are injured. If both unit area and population density are considered, the largest mortality is in the Ohio valley and middle Atlantic states. The small number of deaths in the Gulf Province and the adjoining states, in spite of great thunderstorm activity, has been ascribed by Henry to the sparseness of population and to the milder character of the storms themselves (Fig. 126).

[1] A. J. Henry, "Loss of Life in the United States by Lightning," *U. S. Weather Bur. Bull. 30*, 1901. ("The aim of this paper is to furnish accurate information as to the destruction of human life annually by lightning, to point out the regions where the greatest loss of life occurs, and, so far as practicable, to call attention to a few simple precautions against danger that may be exercised by the individual.") Fig. 126 is redrawn from Henry's report. No later map has been published. A. J. Henry, "Lightning and Lightning Conductors," *U. S. Dept. of Agric. Farmers' Bulletin 367*, 1912. ("Contains information respecting the phenomena of lightning in general, and suggests means of protecting farm buildings from destructive lightning strokes.") A. G. McAdie and A. J. Henry, "Lightning and the Electricity of the Air," *U. S. Weather Bur. Bull. 26, 1899.* (In two parts. The first deals with methods of protecting life and property; the second gives statistics regarding losses.) R. N. Covert, "Modern Methods of Protection against Lightning," *U. S. Dept. of Agric. Farmers' Bull. 842,* 1917. (The object of this bulletin is to "give those persons interested in protection against lightning concise, practical, and up-to-date information accompanied by specifications for installing the equipment so as to secure the greatest degree of protection with the type of installation chosen.") In a recent paper ("Lightning Fire Losses," *M. W. R.*, Vol. 52 (1924), pp. 259–261), R. N. Covert gives two charts, one showing the average annual fire losses caused by lightning and the other the index numbers indicating the relative liability of farm buildings to fires by lightning. It is estimated that the average annual fire loss for the whole United States is over $12,000,000, "probably a conservative figure."

There are certain large facts in relation to lightning which are well established. Isolated houses and farm buildings in the country are more liable to be struck than city buildings. Modern city skyscrapers, with their steel-frame construction, are in themselves excellent lightning conductors. The great networks of wires — telephone, telegraph, trolley, electric light — provided with proper means of conducting discharges to earth doubtless help to prevent many flashes over cities. In general, the nearer people are to the seat of electrical activity,

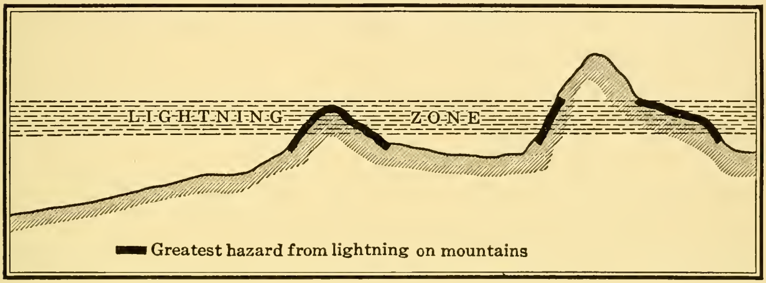

FIG. 127. Lightning Zone in Mountainous Country

the greater is the danger. Therefore the risk of being struck by lightning is greater on mountains, up to a certain height, than in valleys and on lowlands. The "lightning zone" on mountains is at about the level of the base of the thunderstorm clouds. Above and below it there is greater safety. Its altitude varies with the varying conditions of thunderstorm development. It may reach up to the summits of the lower elevations while the higher mountain tops may rise safely above it. Fig. 127 shows diagrammatically the position of this lightning zone in a mountainous country.[1]

The approved modern scientific method of lightning protection consists essentially in inclosing the building in a metal cage or wire network, well grounded. Simple rules for the

[1] F. G. Plummer, "Lightning in Relation to Forest Fires," *U. S. Forest Service Bull. No. 111*, 1912. (This pamphlet brings together "all existing data relating to lightning and trees and arrives at some definite conclusions regarding the relative frequency with which trees are struck, the conditions which tend to produce the greatest danger, and the relative susceptibility of different forms and species." Fig. 127 is redrawn from this bulletin.)

installation of lightning conductors may be found in government and other publications. J. W. Smith made an investigation into the value of lightning rods in protecting buildings in the United States. His conclusion, based on data from about one hundred and thirty mutual fire insurance companies in fifteen states, was that "the efficiency of the lightning rods in preventing lightning strokes is 90 per cent."[1] Whether it is worth while to protect a particular building depends upon its location, the question of fire insurance, the owner's fear of personal injury or loss of life, his willingness to go to additional expense for more safety, his desire to save his property from possible loss by fire, and other considerations. Hundreds of fires in houses and other buildings are started every year by lightning. Nearly all these fires and a considerable loss of human life could certainly be prevented if modern methods of lightning protection were generally employed. In addition to setting fires, lightning often seriously interferes with electric-light, telephone, and trolley services, and temporarily interrupts business. Great quantities of stored oil and of oil from flowing wells have been burned as a result of fires set by lightning.

The vast primeval forests were fire-swept long before the careless camper or lumberman or hunter left his smoldering camp fire to spread over great stretches of valuable timberland, and long before the screaming locomotive threw out its showers of sparks to start the dreaded forest fire. Forest fires are widespread and of frequent occurrence. They cause great loss of valuable wood supply. They occasionally sweep away houses and even villages, and cause loss of life. Sparks from locomotives, and careless campers or tourists start many of these fires, but lightning must be held responsible for a very considerable number. In fact, as shown by the inquiry made by the late F. G. Plummer, lightning ranks second only to locomotives in starting forest fires. Such fires are thus natural results of thunderstorm activity. They are inevitable and un-

[1] J. W. Smith, "Lightning and Lightning Conductors," *Proc. and Papers of the 19th Annual Meeting of the Nat. Assoc. Mutual Insurance Companies, held at Columbus, Ohio, September 22–24, 1914*, pp. 23–42 (an inquiry into the actual losses from fire due to lightning, and into the efficiency of lightning rods in protecting buildings. The data were secured at first-hand from fire insurance companies).

avoidable in their inception. But greater watchfulness will prevent many of them from spreading. Trees are often struck by lightning. They are natural conductors. There are millions of them, and they are often in the lightning zone on mountain slopes. Many trees in the national forests which are especially exposed to lightning show evidence of having been struck several times. It is not true, as this and other facts show, that "lightning never strikes twice in the same place." Plummer has shown that forest fires may result from the ignition of the tree itself, but more often from the ignition of the humus at the base of the tree. It is, however, encouraging to learn that probably not more than 2 per cent of the trees which are struck are set on fire.

The danger of forest fires is greatest in dry spells, in districts of infrequent rains, and at times when the thunderstorm itself does not put out its own fires by a heavy downpour of rain. So-called "dry thunderstorms," with little or no rainfall, such as are common in the mountains of the West and on the Pacific slope, are especially dangerous from the point of view of setting forest fires. A remarkable electric storm occurred in Trinity County, California, on August 1, 1917. The spring and summer had been the driest on record. No rain, or practically none, accompanied these lightning flashes, and eighty forest fires were reported. For almost all of August half the men in the Forest Service in that vicinity were fighting these fires. One forest warden reported that the lightning struck one hundred and fifty times in an area approximately five miles square, and another reported that the country "looked like one vast Christmas tree, as various trees blazed into light on being struck."[1] Over the East thunderstorms are charac-

[1] "Great Thunderstorm of August 1, 1917, in Trinity County, California," *M. W. R.*, Vol. 45 (1917), p. 500. For further details regarding lightning and forest fires see the following: F. G. Plummer, "Forest Fires: their Causes, Extent, and Effects, with a Summary of Recorded Destruction and Loss," *U. S. Forest Service Bull. 117*, 1912; A. H. Palmer, "Lightning and Forest Fires in California," *M. W. R.*, Vol. 45 (1917), pp. 99–102; S. B. Show and E. I. Kotok, "The Occurrence of Lightning Storms in Relation to Forest Fires in California," ibid., Vol. 51 (1923), pp. 175–180 (states that the number of fires set per storm varies from a few up to nearly three hundred and fifty); E. A. Beals, "Discussion of Thunderstorms and Forest Fires in California," ibid., pp. 180–182; E. F. McCarthy, "Forest Fire Weather in the Southern Appalachians," ibid., pp. 182–185; idem, "Forest Fires and Storm Movement," ibid., Vol. 52 (1924), pp. 257–259.

teristically accompanied by heavy downpours of rain, and therefore the fire hazard is greatly reduced. In the Gulf states, for example, although it is estimated that thirty thousand trees are struck annually, the danger from forest fires is comparatively slight. Taking the United States as a whole, the greatest number of trees are struck by lightning in a district including a part of the Colorado plateau, western New Mexico, eastern Arizona, and southwestern Utah. Lightning damage is, however, not solely confined to buildings and trees. Crops occasionally suffer injury from lightning discharges.

CHAPTER XV

TORNADOES[1]

TORNADOES CHARACTERISTIC AMERICAN PHENOMENA · NATURE OF A TORNADO · DAMAGE AND LOSS OF LIFE IN TORNADOES · DISTRIBUTION OF TORNADOES IN PLACE AND TIME · TORNADO WEATHER TYPES · PROTECTION OF LIFE · PROTECTION OF PROPERTY: TORNADO INSURANCE

Tornadoes Characteristic American Phenomena.[2] The most violent atmospheric phenomenon with which man has to contend is the tornado.[3] Its wind velocities are greater than those of the dreaded tropical cyclone. Its strength is superior to that of any structure which man may build to withstand it. In its fullest development it is peculiarly and characteristically American. It finds its real home in the great central lowlands of the eastern portion of the United States. Nowhere else in

[1] The original paper upon which this chapter is based was published in the *Quart. Journ. Roy. Met. Soc.*, Vol. 43 (1917), pp. 317–329. Permission to revise or to reprint this article was very kindly given by the Council of the Royal Meteorological Society.

[2] Those who wish detailed information regarding the characteristics of tornadoes and their relation to human life and to property should consult the numerous publications of Lieutenant (now Colonel) J. P. Finley, U. S. A. These are all listed in the "Bibliography of Meteorology" (see below). For accounts of individual tornadoes which have occurred in recent years reference should be made to the files of the *Monthly Weather Review.* The *Annual Reports of the Chief of the Weather Bureau* and the monthly summaries of *Climatological Data by Sections* also contain notes on tornado occurrence. The newer meteorological textbooks all have chapters on tornadoes, mostly based on Finley's work. Ferrel's "Popular Treatise on the Winds" (1890), chap. vii, devotes several pages to tornado characteristics and to the theory of tornadoes. For a list of publications up to the end of 1889 reference should be made to the following: "Bibliography of Meteorology. A Classed Catalogue of the Printed Literature of Meteorology from the Origin of Printing to the Close of 1881; with a Supplement to the Close of 1889, and an Author Index." Prepared under the Direction of Brigadier General A. W. Greely, Chief Signal Officer, U. S. A. Edited by Oliver L. Fassig (Washington, D. C., 1891). Part IV: Storms (Theory of Tornadoes, Waterspouts, etc., pp. 177–199. Geographical Distribution of Tornadoes, Waterspouts, etc., in the United States, pp. 200–210).

[3] The name "tornado," which is of Spanish origin, was first used to designate the violent thundersqualls of the western coast of equatorial Africa.

the world do tornadoes find equal opportunities for development. Nowhere else are they as frequent, as violent, as destructive as here. They resemble the great summer thunderstorms of the eastern United States in being typically American. Both of these phenomena, therefore, have a truly national interest. They have an importance peculiarly their own.

Nature of a Tornado. The relation of a tornado to human life and property depends upon its nature. What it *does* is determined by what it *is*. Briefly stated, a tornado is a very intense, progressive whirl of small diameter, with inflowing winds which increase tremendously in velocity as they near the center, developing there a counter-clockwise, vorticular, ascensional movement whose violence exceeds that of any other known storm. From the violently agitated main cloud-mass there usually hangs a writhing funnel-shaped cloud, swinging to and fro, rising and descending—the dreaded sign of the tornado. With a frightful roar, as of "ten thousand freight trains," comes the whirl, out of the dark, angry, often lurid west or southwest, advancing almost always toward the northeast with the speed of a fast train (30 to 40 miles an hour or more). Its wind velocities exceed 100, 200, and probably sometimes 400 or more miles an hour; its path of destruction is usually less than a quarter of a mile wide; its total life is a matter of perhaps an hour or less. It is as ephemeral as it is intense. In semi-darkness, accompanied or closely followed by heavy rain, usually with lightning and thunder and perhaps hail, the tornado does its terrible work. Almost in an instant all is over. The hopeless wrecks of buildings, the dead, and the injured lie on the ground in a wild tangle of confusion. The tornado has passed by. It is spinning away toward the northeast, perhaps to carry destruction to other peaceful towns and scattered farmhouses which lie in its path. In the torrential downpour of rain the work of rescue is hindered, and property damage and loss of life may be still further increased.

Fortunately for man tornadoes are short-lived, have a very narrow path of destruction, and are by no means equally intense throughout their course. Their writhing funnel-cloud, which indicates the region of maximum velocity of the whirling

winds, ascends and descends irregularly. Sometimes it may be seen traveling along with its lower end at a considerable distance aloft, like a great balloon. The tornado is then in the clouds, its natural home. Again, under other conditions, the funnel-cloud works its way downward to the earth like a huge gimlet, its base enlarged by the débris drawn in by the inflowing winds, its violence so intense that nothing can resist it. Where the funnel-cloud descends, the destruction is greatest; where it rises, there are zones of greater safety. The whirl may be so far above the ground that it does no injury whatever. It may descend low enough to tear roofs and chimneys to pieces. It may come down to the ground and leave nothing standing. Thus man need not despair of his life or give up hope for his property even if a tornado is apparently moving directly toward him. He may be far enough away from the vortex to experience only the gentlest of breezes. He may happen to be in a portion of the tornado track where the whirl is relatively weak or where the violence is all aloft.

It is one of the most remarkable things about a tornado that at even a very short distance—perhaps only a few yards—from the area of complete destruction close to the vortex, even the lightest objects may be wholly undisturbed. This restricted area of destruction is well illustrated in one of Finley's early diagrams, in which the comparative force of the winds within the storm's path, at different distances east and west of the center of the Pipe Creek, Kansas, tornado of May 30, 1879, is shown. (Fig. 128.)[1]

Damage and Loss of Life in Tornadoes. The central low pressure core of the tornado is surrounded by radially inflowing winds of moderate strength, and then, closer to the center, by spiraling and ascending winds of terrific violence, strong enough to crush and wreck the strongest buildings and ascending with sufficient velocity to carry aloft objects so heavy that for wind to lift them seems almost impossible. The surface winds which take part in the vorticular inflow and ascent seem to be chiefly

[1] J. P. Finley, "Report of the Tornadoes of May 29 and 30, 1879, in Kansas, Missouri, Nebraska, and Iowa," *U. S. Signal Service Professional Papers*, No. IV, 1881, Fig. 7.

responsible for property damage and loss of life. There is, however, an additional factor. The central core, surrounded by its whirling winds, has its pressure greatly reduced by the centrifugal force of the whirl. It therefore exerts a powerful explosive effect upon air near it at ordinary pressures, within buildings or in other more or less well-inclosed spaces. This

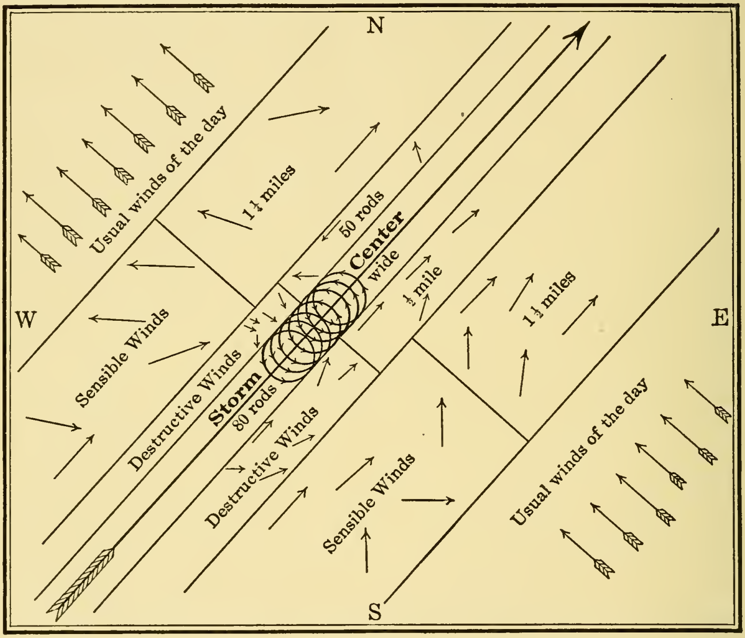

FIG. 128. Winds of Tornado of May 30, 1879

curious but very widely attested explosive effect accounts for many tornado "freaks" which cannot be explained by any controls, either of radially or spirally inflowing winds, whatever their velocity. If to these two general conditions there are added the further facts of the varying intensity of the tornado, the ascent and descent of its funnel-cloud, and the fluctuating velocity of its winds, it is no longer difficult to believe the many remarkable stories of the destruction wrought by these storms. Incredible as they seem, most of these accounts are probably not exaggerated.

The damage done by tornadoes may be roughly classified as follows: (1) that resulting from the violence of the surface winds, blowing over buildings and other exposed objects, crushing them, dashing them against each other, etc.; (2) that caused by the explosive action; (3) that resulting from the uprushing air movement close around the central vortex. Carts, barn doors, cattle, iron chains, human beings, are carried through the air, whirled aloft, and dashed to the ground, or they may be dropped gently at considerable distances from the places where they were picked up. A horse has been carried alive for over two miles. Iron bridges have been removed from their foundations. A cart weighing six hundred pounds has been carried up in a tornado, torn to pieces, and the tire of one wheel found thirteen hundred yards away. Beams are driven into the ground; nails are forced head-first into boards; cornstalks are driven partly through doors. Harness is stripped from horses, and clothing is torn from human beings and stripped into rags. In one place the destruction may be complete, with every building and tree and fence leveled to the ground. A few feet away the lightest object may be wholly undisturbed. The damage is greater, and extends farther from the center, on the right of the track than on the left, for the wind velocities are greater on the right, as in the dangerous semicircle on the right of the track of tropical cyclones.

The explosive effects are many and curious. The walls of buildings—one or more of them—fall out, sometimes letting the roof collapse on the foundations; or the roof may be blown off, leaving the walls standing. The surface of the ground is swept clean, as if with a broom. Articles may be blown out of houses and carried to great distances. Empty bottles are uncorked; feathers are plucked from barnyard poultry; doors and windows are blown out; soot rises from chimneys; mud penetrates into clothing. In the Omaha (Nebraska) tornado of Easter Sunday, 1913, some bedclothes were drawn toward a fireplace and then up the chimney. A good illustration of the explosive effect is given in a story which dates back a good many years. A railroad agent, after a train had passed, left his station, locking the door and closing the shutters of the

window. A tornado happened to travel by, very near the station, and when the agent returned he found that the window had burst open outward.

The violence of the ascending air near the center of the tornado is sufficient to carry up very heavy objects of all kinds. These may often be seen, from a safe distance, rising and whirling around the vortex and then falling to the ground when they are thrown out of the grasp of the rising currents. There is a story of a man who was whirled aloft in a tornado. In his terror he clutched at an object which was whirling along close to him. When he was dropped to the ground, in this case uninjured, his hand was full of horsehair. The explanation is that the man and a horse were traveling together in the grasp of the ascending vortex, and as a drowning man traditionally clutches at a straw, so this man seized the nearest object, which happened to be the horse's mane or tail. When barn doors and trees and beams and human beings and cattle can be whirled up in the air, we must be dealing with a phenomenon of tremendous power. It is easily understood how light objects may be carried several miles from their starting-point. Clearly, also, rain cannot fall where the ascending movement is most active, but the precipitation will occur around the central whirl, in front, behind, or to one side of the tornado.

Property damage in the United States due to tornadoes varies greatly from year to year, depending, as it does, upon the "accidental" passage of tornadoes through well-populated or through sparsely settled districts. In half an hour the St. Louis tornado (May 27, 1896) destroyed property to the amount of $10,000,000 in St. Louis alone. In some years the damage for the whole United States falls to a few hundred thousand dollars. Henry has estimated that the average annual loss during the period 1889–1897 was about $1,000,000. This average does not include two cases of unusually heavy damage.[1]

Figs. 129 and 130, taken from Finley's reports, illustrate some of the vagaries of tornadoes, especially in relation to

[1] A. J. Henry, "Climatology of the United States," *U. S. Weather Bur. Bull. Q* (1906), pp. 76–80. Also "Property Loss by Tornadoes during the Period 1889–1897," *Annual Report of the Chief of the Weather Bureau for 1897–1898* (1899), p. 304.

human life.[1] Fig. 129 (Buffalo Creek, Kansas, tornado, May 30, 1879) shows a more or less typical case. The arrows indicate the direction of the winds by which several buildings were more or less injured. A laborer coming out of the east side of a barn was caught by the wind, carried halfway around the building, and then set down, very dizzy but otherwise uninjured. Two horses close by were stripped of their harness, which was literally torn to pieces. One horse was killed; the other was so much injured by flying débris that he bled to death. A scantling 4 inches square and 10 feet long was driven $3\frac{1}{2}$ feet into the ground some distance from its starting-point. A large board (identified by its color) 16 feet long and 1 foot wide was found two miles to the northeast, not broken or split and with the nails still in it.

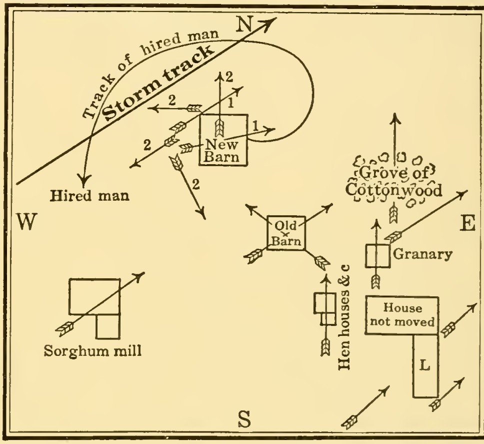

FIG. 129. Tornado Damage, May 30, 1879

Fig. 130 illustrates the tragic fate of one family in a tornado on May 30, 1879. A house was moved entirely from its foundation to the southeast, then broken to pieces and scattered along the tornado track to the northeast for over a mile. A group of trees only 65 feet southwest of the house was uninjured, but the trees in a grove east and south of the house were partially bent to the ground, stripped of bark and foliage, and their southwestern sides looked as if they had been burned. The members of the household, consisting of father, mother, and four children, ran outdoors as the storm came. They first turned northwest, but thinking that the tornado was coming toward them they turned toward the east. One by one they

[1] J. P. Finley, loc. cit. in footnote, page 345; Figs. 19 (p. 32) and 7 (p. 93).

were caught up and carried by the wind. The father and baby were carried 150 yards into a field to the northeast, covered with mud and bruises, and found in the agonies of death. The mother, who was nearer the house, was carried eastward 75 yards, and dashed against a tree around which she was partially twisted; her skull was crushed, and her clothing stripped from her body. A girl was found dead 50 yards northeast of the house, in the direct path of the storm.

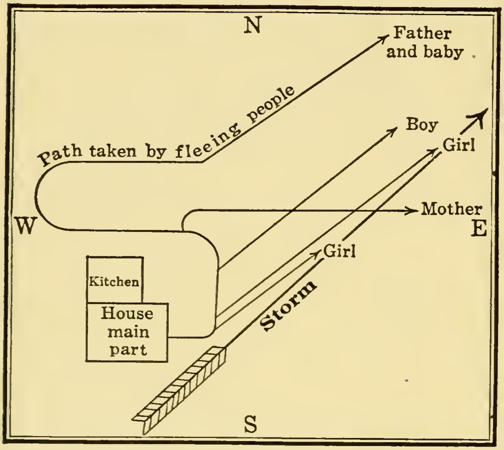

FIG. 130. A Tornado Tragedy, May 30, 1879

A boy was blown into a haystack 45 yards to the northeast, and a girl was found 80 yards to the northeast, lying in the tornado track. Neither of these two children was seriously injured. The ground on which the house had stood was swept clean, as if by fire. Disasters similar to this one come all too frequently in the tornado belt.

Finley listed some 600 tornadoes, of which 40 were fatal to human life, causing a loss of 466 lives and injuring 687 persons.[1] Henry has listed the tornadoes which caused a loss of life of 45 or more and occurred between April, 1880, and June, 1903.[2] As is to be expected, each one of these tornadoes crossed a

[1] J. P. Finley, "Report on the Character of Six Hundred Tornadoes," *U.S. Signal Service Professional Papers*, No. VII, 1884. (Gives tabulated statistics, with map, showing the distribution of tornadoes in the United States for 1794 to 1881. One criticism which may be made of the map is that it dates back to a time (1794) when very few people were living in the states away from the Atlantic seaboard. Hence the tornado frequency in the then more densely populated states is probably exaggerated. Further, the extension of the region of fairly high frequency to the coast of Georgia may possibly indicate a failure on the part of the early observers to distinguish between hurricanes and tornadoes.)

[2] A. J. Henry, *Bull. Q*, pp. 78–79.

town or an otherwise thickly settled community. In the case of the St. Louis tornado (May 27, 1896) the loss of life was 306. Henry states that not more than three or four "really destructive" tornadoes occur in the United States each year. Harrington estimated the possible danger to life as follows:[1] The area of destruction is seldom greater than 1 square mile. About 50 tornadoes occur a year, and about 20 do considerable damage. Therefore 20 square miles, more or less, are thus affected. The region in which tornadoes are likely to occur embraces 1,250,000 square miles. The chance that a tornado may in any year cross the particular locality where any individual may happen to be is $\frac{1,250,000}{20}$. This is one chance in 625,000, and is "not worth worrying about."

Distribution of Tornadoes in Place and Time. The real home of the tornado is over the great lowlands of the central and upper Mississippi and lower Missouri valleys and, to a less marked degree, over some of the Southern states. Tornadoes are rare west of the 100th meridian, and very rare or unknown in the mountain areas. They have been reported from all states east of the Plains, but decrease markedly in frequency toward the north. Kansas, Missouri, Nebraska, Iowa, Indiana, Illinois, Ohio, are states in which records show that a considerable number of tornadoes have occurred. They are rare in the Appalachian Mountains and also along the Atlantic and Gulf coasts. A map showing the distribution of tornadoes is apt to be more or less misleading. Violent thundersqualls have doubtless often been reported as tornadoes, and perhaps still occasionally are so reported. Again, many real tornadoes must have occurred, more often in the past than today, where there were no observers to report them. Thus, such a map of tornado frequency as that prepared some years ago by Finley, useful as it is in giving a general idea of the geographical distribution of tornadoes, must not be taken too literally.[2] The widespread

[1] M. W. Harrington, "About the Weather" (1899), p. 164.

[2] J. P. Finley, loc. cit., footnote 1, page 350. The tornadoes reported between 1889 and 1896 have been listed and charted by Henry, together with data regarding loss of life and property damage (A. J. Henry, "Tornadoes, 1889–1896," *Annual Report of the Chief of the Weather Bureau for 1895–1896* (1896), pp. xxiii–xl, Charts

impression that tornadoes are increasing in number in the United States is without foundation of fact. Tornadoes are reported with greater accuracy than formerly, and they are likely to do more damage than they used to, because the country is more densely populated.

As to time of occurrence, tornadoes may appear in any month and at almost any hour of the day or night. Like thunderstorms, however, they distinctly prefer the warmer months, and the hours closely following the warmest part of the day. Thus spring and early summer, and from 3 to 5 P.M., are their favorite times. The thunderstorm belt is also the tornado belt. Hence, with the northward progression of the sun in the spring, tornadoes have an earlier season in the South and a later season in the North. In fact, in the Gulf Province and the adjoining states, they may occur in the warmer spells of the winter and spring months. Farther north the time of greatest frequency is in early summer or in midsummer.

Tornado Weather Types. Tornadoes have much in common with thunderstorms. In fact they are in reality special local developments, of greater violence, in connection with severe thunderstorms. The general conditions which produce these two phenomena are to a large extent identical. The essential difference comes in the formation of the vorticular whirl in the tornado. Thus, like the largest and most severe thunderstorms, tornadoes occur as attendants of the parent cyclones of which they are the offspring. They are born, in the large majority of cases, in the area of warm, damp southerly winds flowing northward from the Gulf of Mexico in front of a general cyclonic storm. This storm is usually more or less elliptical or V-shaped, its major axis extending north to south or northeast to southwest from the Great Lakes, across the central

I–VIII). According to H. C. Hunter, in the nine years 1916–1924 inclusive 876 tornadoes are known to have occurred, resulting in the loss of 2242 lives and damage to property to the value of about $92,000,000 (*Bull. Amer. Met. Soc.*, Vol. 6 (1925), pp. 42–43). On the afternoon of March 18, 1925, portions of southeastern Missouri, southern Illinois and Indiana, and neighboring sections of Kentucky and northern Tennessee suffered tornado damage of unusual severity. About 800 lives were lost; nearly four times as many persons were injured, and the damage to property was not far from $20,000,000. Several towns were completely obliterated.

lowlands well into the Southern states. The wind-shift line is usually well marked. North and west of the wind-shift line northerly to westerly winds are blowing, with relatively low temperatures and not infrequently with rain or snow. South and east of the critical axis there is a great flow of southerly or southwesterly winds, with higher temperatures, usually sultry and oppressive weather, and often with rain squalls. When conditions are favorable, tornadoes are likely to occur in a district some 300, 400, 500, or more miles to the southeast, south, or southwest of the cyclonic center, near to the wind-shift line, but usually to the east of it. Here the contrast between the warm, damp southerly and the cool, dry northerly and westerly winds is sharp. Here is inevitably a zone of great disturbance; of overrunning, underrunning, and mixing; of turbulence; of instability; of local whirls. Here, aided by the local warming due to sunshine, are favorable conditions for breeding thunderstorms and, fortunately much less often, for developing tornadoes. The parent cyclone may travel many thousands of miles, a good part of the way around the world; yet in only one portion of its long course, in the Mississippi Valley region, and usually only during a part of the year, in late winter, spring and summer, is just the right combination of conditions attained for developing the dreaded tornado. Fig. 131 is a free-hand composite, showing, in a broadly generalized way, a weather map characteristic of tornado occurrence in the central Mississippi Valley region of the United States. Tornadoes also spring up under conditions which differ considerably from those here illustrated. It is therefore impossible to select or to draw any fixed tornado type map which will inevitably and invariably bring tornadoes. Many weather maps for days on which notable tornadoes occurred have been reproduced.[1]

It is natural and unfortunate that when once the proper con-

[1] Thus, in the *Atlas of Meteorology*, Plate 33, there are given maps for the tornadoes of February 19, 1884, for the Louisville tornado of March 27, 1890, and for the St. Louis tornado of May 27, 1896; and in Milham's "Meteorology," Charts XXXVI and XXXVII, the weather maps for March 11, 1884, and April 25, 1906, both days on which tornadoes occurred, are reproduced. Numerous tornado type weather maps have also been included in the descriptions of special tornadoes in the *Monthly Weather Review*.

ditions have been established, several tornadoes may develop over the same general region. They usually occur in groups or series, perhaps more or less simultaneously, perhaps in succession, and all moving along essentially parallel paths. This seems to be especially the case in spring. February 19, 1884, was the most remarkable and the most disastrous tornado day on record. Some sixty tornadoes occurred, mostly in the

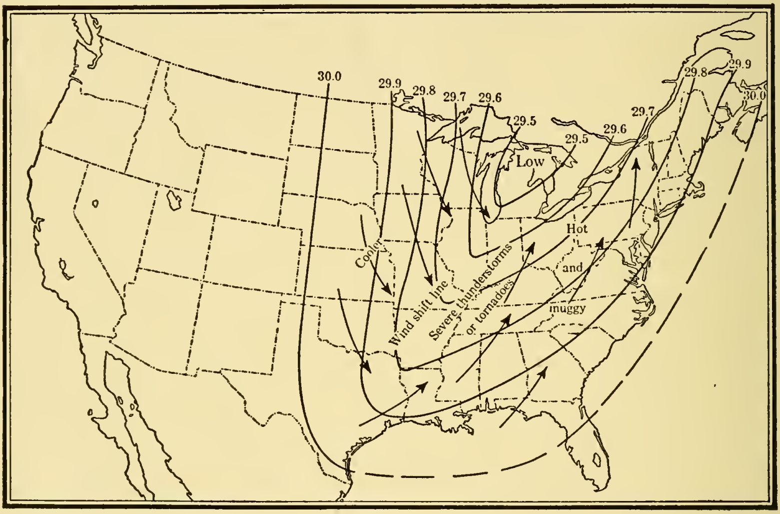

FIG. 131. Composite Weather Map, showing Conditions Favorable for Tornadoes

Southern states. The loss of life was 800. In addition, fully 2500 persons were wounded and over 10,000 buildings were destroyed.

Protection of Life. Tornadoes are very frightful phenomena. They inevitably inspire terror in all who are in their vicinity. The possible protection and preservation of human life in tornadoes is a very real and vital question over large areas of the United States. Fear is inevitable; but unnecessary fear, harassing millions of people, many days each year, is most regrettable. Those who live in the tornado belt may well remember that really destructive tornadoes are rare; that their paths are very narrow; that they are short-lived; that they are not everywhere equally violent, and may pass overhead

without doing the least damage on the earth's surface. Again, many persons who are actually caught up by the tornado winds are not in any way injured. Harrington put the case as follows: "Those who live in the region affected may calm themselves with the reflection that, taken altogether, there is not one chance in a million, though they lived one hundred years, that they will be injured by a tornado." And the late Cleveland Abbe, taking the tornado statistics for 1874–1881 and for 1889–1896, computed the tornado frequency per unit area; that is, made allowance for the relative areas of the different states and of the tornadoes themselves.[1] His conclusion was that even in the so-called tornado states the probability that any specific area or farm of the size of one square mile will be struck by a tornado is less than one sixteenth of 1 per cent per century. This makes the probability of tornado destruction less than that of lightning or fire.

From his long and intimate study of tornadoes Finley deduced certain rules for the protection of human life which have over and over again proved their accuracy and value. If a tornado is approaching from west or southwest, and the observer is on or very near its probable path, the best thing to do, if there is time, is to run *north*; never east, northeast, or southeast. "Dug-outs," or tornado cellars, should be provided near the house, as in the yard, or close by in a field, or on the north or east slope of a hill close by. The roof should be level with the ground (in fact it is best formed by the ground itself, the top of the cave being as much as three feet below the surface), and should be supported by timbers. If the dug-out is under the house, it should be in the west wall of the cellar. Ventilation may be provided through the roof of the dug-out or through the door, which ought to be covered with iron grating. The safety provided by dug-outs is that they remove persons who seek refuge in them from risk of injury from flying débris, also from the danger of being picked up by the winds.

Should there be no dug-out or cellar-cave available, the best thing to do is to leave the house and run north of the approach-

[1] Cleveland Abbe, "Tornado Frequency per Unit Area," *M.W.R.*, Vol. 25 (1897), pp. 250–251.

ing tornado. If there is no time to escape, or if escape is for any reason impossible, the safest place is to stand, face forward, against the west or south wall of the cellar, as near the southwest corner as possible. The reason for these precautions is that the débris of the house, if the building is destroyed, will be most likely to be carried toward the northeast. Hence northeast or east rooms and walls are least safe. In the Omaha tornado of 1913 the greatest damage to houses was done to those on northeast slopes. The lower floor of a house (west or south wall) is safer than any higher story, but the cellar is the best place of all. Groves of trees or orchards are especially unsafe because of the danger of the falling trees. If caught outdoors, and otherwise unable to escape, the best thing to do, as a last resort, is to lie flat on the ground in an open space, face downward, the head to the east, and the arms placed over the head for protection. Stock should, if possible, be driven north of the probable track if the tornado seems likely to pass centrally over one's location, and to the south if the storm shows signs of passing by on the north. Cattle are safer outside a barn than inside.

Finley has very clearly stated the situation regarding the possibility of erecting tornado-proof buildings as follows:

> It matters not how you construct, or of what material, if your building rises above the surface of the earth (which it must necessarily do), it thereby offers obstruction to the advance of the tornado cloud, and it will go, either from the foundation or into kindling wood and a distracted mass of bricks and mortar, in spite of the propagation of any theory or the possibilities of architectural skill. . . . If buildings are in the line of its (the tornado's) destructive path, whether upon a hill, in a valley, or within a ravine, they are liable to be subject to its violence.

The foregoing rules, here briefly summarized, will be found in much greater detail in Finley's writings. They have proved their value in countless cases, and are the immensely important and very practical result of the exhaustive study of tornadoes which Finley carried on during several years.

Protection of Property: Tornado Insurance. In regard to the protection of property certain things are fairly clear. Torna-

does cannot possibly be prevented. And no building, certainly none of any practical use, can be built to withstand the violence of the wind in the vortex of a well-developed tornado. Hence the only resource left is to protect life and property to the best of man's ability, and with a knowledge of the facts which have been brought to light by a sane, unprejudiced, scientific study of these phenomena. Owing to the varying intensity of tornado violence and of the velocity of the surface winds the damage done to different sorts of buildings varies greatly. If the intensity of the storm is not sufficiently great to destroy everything in its path, the damage done by the less violent winds will obviously depend largely upon the strength of construction and upon the building-materials. It was Finley's advice to build "as you would without the knowledge of a tornado." He found, however, that other things being equal a frame building seems to resist destruction better than one of brick or stone. The modern steel-construction buildings have some of the "elastic" quality which renders frame structures safer than the more stable and solid ones of stone or brick of the older style. Topography apparently has no effect upon the movement of a tornado once it is started. Therefore it makes little or no difference, in the end, whether a building is in a valley or on a hill.

As to tornado forecasts, the weather map conditions favorable for the development of tornadoes are as a rule so well marked that the official forecasts seldom fail to note the probable occurrence of severe local storms over the districts which are threatened. The word "tornado" is not used in these forecasts.[1] Barometers in the hands of individual observers are of no assistance in detecting tornado conditions.

In view of the property loss occasioned by tornadoes, it is but natural that tornado insurance has become a widespread and popular method of financial protection. So far, however, the business has not been carried on upon a thoroughly scientific basis. Tornado insurance to the amount of several hundred millions of dollars is carried largely by general fire insurance

[1] Cleveland Abbe, "The Prediction of Tornadoes and Thunderstorms," *M. W. R.* Vol. 27 (1899), pp. 159–160.

companies and partly by local mutual companies. The definition of a tornado is often crude and unscientific, and there is much unnecessary confusion. It is true that the more conservative companies do prohibit some risks, such as windmills, old and frail buildings, large plate-glass windows, and the like. One result of this is that windmill insurance companies have been organized which insure good windmills at $1 a year. It is interesting to note the marked rise and fall of the amount of tornado insurance with the occurrence, in any year, of severe or destructive tornadoes. Closely following the St. Louis tornado of May, 1896, there was an increase of tornado insurance of nearly $10,000,000; and after the Omaha tornado of Easter Sunday, 1913, several million dollars' worth of tornado insurance was written in Omaha and the surrounding districts, which were at once thoroughly canvassed by insurance agents. Many new dug-outs and cellar-caves were built at the same time.[1] As H. E. Simpson has pointed out, tornado insurance risks differ from others in several ways, notably in the fact that there is no criminal hazard present.[2] For people cannot blow away or explode or destroy their buildings for the sake of the insurance on the plea that the damage was done by a tornado. A more careful scientific study of tornado occurrence and of tornado risks in different parts of the United States on the part of insurance companies would enable these companies to predict their risks and adjust their premiums accordingly, on a more just and more rational basis, to the mutual advantage and security of both insurer and insured. It is obviously wise to scatter tornado risks across, not along, the usual path followed by tornadoes. The complete destruction often caused by a single tornado makes it extremely unsafe for any local mutual insurance company to insure over a small area only, where the loss occasioned by one tornado may ruin the company. On the whole, general tornado insurance in the tornado belt, and buildings erected without regard to the possibility of tornado occurrence, seems to be the wisest policy.

[1] G. E. Condra and G. A. Loveland, "The Iowa-Nebraska Tornadoes of Easter Sunday, 1913," *Bull. Amer. Geogr. Soc.*, Vol. 46 (1914), pp. 100–107.

[2] H. E. Simpson, "Tornado Insurance," *M. W. R.*, Vol. 33 (1905), pp. 534–539 (a short bibliography is appended).

CHAPTER XVI

COLD WAVES, NORTHERS, AND BLIZZARDS

BEGINNINGS OF AN UNDERSTANDING OF COLD WAVES · DEFINITION OF A COLD WAVE · GENERAL DESCRIPTION OF A COLD WAVE · FACTORS FAVORABLE TO COLD WAVES · SOME ECONOMIC ASPECTS OF COLD WAVES · INSTRUMENTAL RECORDS OF COLD WAVES · WEATHER MAP TYPES FAVORABLE FOR COLD WAVES IN THE EASTERN UNITED STATES · TEMPERING EFFECT OF THE GREAT LAKES · COLD WAVES OF THE WESTERN UNITED STATES · AMERICAN COLD WAVES COMPARED WITH THOSE IN OTHER COUNTRIES · THE TEXAS NORTHER · THE BLIZZARD

Beginnings of an Understanding of Cold Waves. In 1846 William C. Redfield, one of the brilliant group of American meteorologists of the middle and latter portion of the nineteenth century, wrote:[1]

> It will be readily seen that on the approach of a great storm from the lower latitudes by the usual routes, while revolving from right to left, its first effect will be to bring in the warm and humid air of a more southern region; and when the axis of the gale has passed, the contrary result necessarily follows. . . . Indeed, this rising of the thermometer during the access of winter storms, and its great depression as they pass off in their northeasterly courses, might in itself afford us good proof of the storm's rotation, were more direct evidence wanting.

The real beginning of an understanding of American cold waves is found in this statement. In July, 1861, in a remarkable letter written by Joseph Henry, then Secretary of the Smithsonian Institution, to General Sabine, the first use of the term *wave* occurs in connection with the advance of winter cold spells across the eastern United States:

[1] W. C. Redfield, "On Three Several Hurricanes of the Atlantic and Their Relations to the Northers of Mexico and Central America, with Notices of Other Storms" (New Haven, 1846), pp. 102, 104. The papers collected in this publication first appeared in the *American Journal of Science*.

We find that not only do the storms of wind and rain come to us (at Washington) from the west, and enter our territory from the north (near the Rocky Mountains, in British possessions, about 110° west), but also the cold and warm periods. The early and late portions traverse the country in the form of a long wave extending from north to south, and moving eastward. When this wave arrives at a given meridian during the night, a killing frost is experienced along a band of country extending north and south, it may be in some cases more than a thousand miles, while in an east and west direction it is not more than fifty or a hundred miles.[1]

"From the observations made at this institution," Henry further said, "the waves, as it were, of cold which reduce the temperature of the United States frequently begin several days earlier at the extreme west."[2] Further, speaking of a forthcoming volume of meteorological observations to be published by the Smithsonian Institution, the Secretary said:[3]

This volume will also contain special thermometric observations at stations distributed over the area extending from the Arctic regions to the northern states of South America; and from the Pacific to the Atlantic coast, for the purpose of showing the progress of cold periods across the continent, from the Rocky Mountains to Bermuda.

Thus, a decade before the publication of the first regular daily weather maps for the United States, the eastward progression of *waves* of cold from the Rocky Mountains to the Atlantic coast was clearly recognized. Indeed, as far back as

[1] The present writer has been unable to find either the original letter from Professor Henry to General Sabine, or the first printing of it. Through the courtesy of Dr. Charles D. Walcott, the present Secretary of the Smithsonian Institution, a search was made and no record was found of the letter, which may have been destroyed with practically all the other records of the Institution in the fire of 1865. The meteorological material at the Smithsonian Institution was later turned over to the Signal Office of the United States Army, after the establishment of the government meteorological service in 1870. Professor C. F. Talman, librarian of the United States Weather Bureau, very kindly made a search through the files of the Bureau, but without success. The quotation here given is taken from Fitz Roy's "Weather Book" (p. 137), where Professor Talman informed the writer that the letter was printed. Curiously enough, the letter is not found in the two volumes of Henry's scientific writings published in 1886 by the Smithsonian Institution.

[2] *Ann. Rept. Smithson. Instn. for 1861* (1862), p. 20.

[3] Ibid., p. 37.

1793 emphasis was laid on the greater frequency and severity of winter cold spells in New England than in corresponding latitudes in Europe, although the low temperature was wrongly attributed to the descent of the northwest winds from the Appalachian Mountains, and there was, naturally, no recognition of the cyclonic control over these winds.[1] The importance of cold waves in relation to agriculture, transportation, and other interests has naturally led to a considerable study of these phenomena, chiefly from the point of view of the forecaster.[2]

Definition of a Cold Wave. Not every considerable and sudden fall of temperature in the United States is a cold wave. For forecasting purposes it is necessary to define certain limits, both of time and temperature fall. A cold wave according to the official definition adopted by the United States Weather Bureau is a drop of a certain number of degrees of temperature within twenty-four hours, with a minimum falling below a

[1] Samuel Hale, "Conjectures of the Natural Causes of the Northwest Winds being Colder and more Frequent in the Winter in New England than in the same Degrees of Latitude in Europe," *Mem. Amer. Acad. Arts and Sciences*, Vol. 2 (1793), pp. 61–63.

[2] Lists of notable cold waves may be found in Lorin Blodget's "Climatology of the United States" (1857), A. W. Greely's "American Weather" (1888), pp. 216–222, and E. B. Garriott's "Cold Waves and Frost in the United States," *U. S. Weather Bur. Bull. P*, 1906. (The last-named publication "notes briefly the general distribution of the colder areas of the northern hemisphere, refers to general conditions that are associated with cold waves, and presents a chronological account of historical cold periods in the United States. It then summarizes and classifies the more important cold waves and frosts that occurred from 1888 to 1902 inclusive, and presents 328 charts that exhibit the meteorological conditions that attended the principal cold waves of that period.") Reference may also be made to A. J. Henry, "Climatology of the United States," *U. S. Weather Bur. Bull. Q*, 1906, and, for a recent discussion of cold wave forecasts, to "Weather Forecasting in the United States," *U. S. Weather Bur. No. 583*, 1916. (H. J. Cox contributes the general discussion of cold waves (chap. vi, pp. 143–176), which is illustrated by weather maps typical of various cold wave conditions. Fig. 66, p. 148, shows the number of cold waves which occurred between 1904 and 1914 inclusive. There are also shorter papers by the district forecasters on the cold waves of the different sections.) The *Monthly Weather Review* regularly contains discussions of cold waves as they occur, often illustrated by special weather maps. Several pamphlets issued by the United States Department of Agriculture have discussed the subject of frost and of cold waves and have indicated methods of protection against frost and cold. See, for example, E. B. Garriott, "Notes on Frost," *U. S. Dept. of Agric. Farmers' Bull. 104*. An early publication on cold waves is T. M. Woodruff's "Cold Waves and Their Progress," *U. S. Signal Service Notes*, No. XXIII, 1885.

fixed temperature. The amount of drop, and also the minimum, are different for different sections and for different seasons, the definite values in each case having been arbitrarily fixed with a view to securing the best possible protection for agricultural and commercial interests.

Fig. 132 shows the required temperature falls (within twenty-four hours) and the minimum temperatures necessary to give a

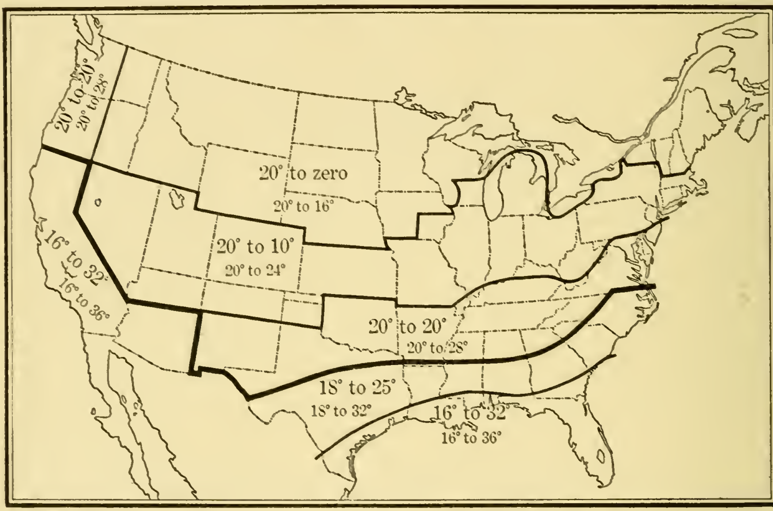

FIG. 132. Cold Wave Chart

cold wave, according to the official definition of the Weather Bureau. The upper larger figures are for winter; the lower for the other months. Above the heavy line the winter months include December, January, February, and March; below the line they include December, January, and February. It is to be observed that the cold wave is simply a certain condition of temperature, and the definition has nothing whatever to do with the wind. In the popular mind, however, the wind which brings the cold and the cold itself are always thought of as constituting the cold wave. The amounts of fall of temperature are the same in all seasons for each individual district, but the limiting minima vary, being lower in winter and higher

during the rest of the year. These minima, furthermore, are not as far below the normal in the North as in the South. Along the Gulf and southern Pacific coasts, for example, where crops are growing the year round, temperatures below freezing are dangerous at any time. The limiting temperatures being but slightly below the normal in the North, and much below normal in the South, the number of cold waves recorded in the North is naturally much greater than that recorded in the South. The cyclonic conditions favorable for cold waves are also more frequent along and near the Northern border.

General Description of a Cold Wave. For severity, suddenness, and frequency of occurrence the cold waves of the eastern United States are unique. They are typically American phenomena. As first pointed out by Redfield, they are a characteristic feature of the rear of winter cyclonic storms, and follow warmer weather, accompanied by winter rains or snow, in front of the low pressure center. Following the passage of the center, especially when there is a well-developed high pressure area in the Northwest and the wind-shift line is well developed, the cold wave is heralded by a sudden shift of the wind to the west and northwest—a piercing blast, sweeping down from the cold continental interior of western Canada, reducing the temperature 20°, 30°, 40°, or even more, within twenty-four hours. The drop in temperature often begins before the rain or snow has ceased falling. If it is still raining when the westerly wind begins to blow, the rain quickly turns to sleet, and an icy covering forms on all objects outdoors. If it has been snowing, the snow soon becomes hard and dry. The wheels of passing vehicles, the runners of sleighs, and the footsteps of pedestrians "sing" with a metallic sound. The ice on rivers and lakes tightens its grasp, and cracks and "booms" with a reverberating sound. The collars of greatcoats are turned up; hands are put into muffs or pockets; people walk more briskly; every preparation is made for a spell of hard cold weather.

The northwest wind blows with considerable velocity for a day or more, accompanied by clear skies and bright sunshine, and then gradually diminishes. While the cold is more keenly

felt during the blowing of the strong wind, the actual minimum temperatures are recorded on the two or three or perhaps more calm, clear nights which follow, in the central portion of the anticyclone. Under these conditions nocturnal radiation fogs are common. The cold wave proper is therefore not at the center of the high, but on its southeastern margin and to the southwest of the preceding low, in the area occupied by the northerly and northwesterly winds.

From their northwestern origin the areas of cold, usually more or less elliptical in shape with the longer axis extending southwest-northeast and covering hundreds of thousands of square miles in extreme cases, progress in a general easterly or southeasterly direction toward the Atlantic or Gulf coast, but with much diminished intensity as they enter warmer latitudes and increase their distance from their frigid northern source. In Fig. 133 the "cold wave axis" shows the middle frontage of cold waves as they come down from the Northwest in the winter months, as plotted by Bigelow.[1] The axes of certain characteristic types of individual cold waves, greatly generalized, are indicated (following J. P. Finley) by the heavy lines, the direction of progression being shown by the arrowhead. The rate of advance is determined by the rate of progression of the controlling cyclonic and anticyclonic pressure systems. A cold wave may easily sweep over the country from the northern Plains to Texas or to the Atlantic coast in two or three days. As it advances, it gradually becomes less severe, especially (1) if the ground is not snow-covered; (2) in the early spring, and (3) during the daytime, when the increasing warmth of the sun is able to warm the earth's surface more effectively. The lower air may then become more or less unstable. Convectional overturnings, flurries, and eddies occur. The wind blows with a somewhat higher velocity during the day. If, on the other hand, the northwest wind blows at night over a snow-covered surface, the temperature of the lower stratum may be somewhat reduced as the cold wave sweeps forward on its course.

[1] F. H. Bigelow, "Storms, Storm Tracks, and Weather Forecasting," *U. S. Weather Bur. Bull. 20*, 1897; reproduced in the *Atlas of Meteorology*, Plate 28.

It is fairly safe to expect, on the average, three or four severe cold waves every winter in the eastern United States; but such intense cold spells do not, as a rule, last longer than two or three days, except over the northern Plains, and are naturally more frequent in the North than in the South. After about the middle of February the duration of these "cold snaps," as they are often popularly termed, usually lessens perceptibly.

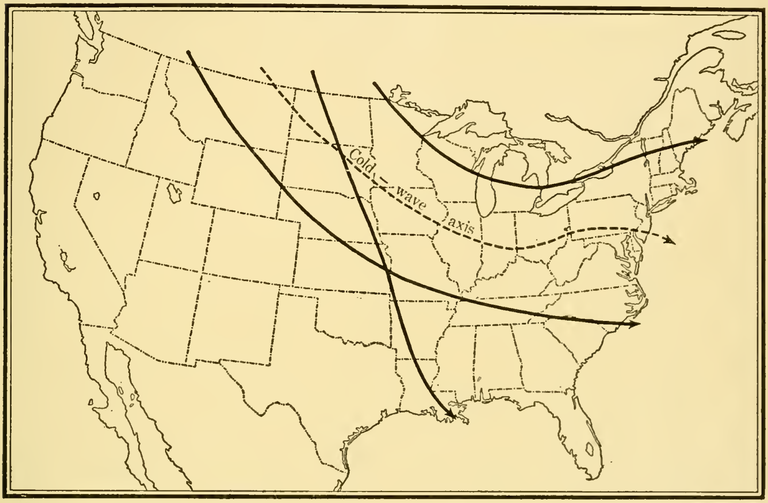

FIG. 133. Cold Wave Axis and Generalized Paths of Cold Waves across the Eastern United States

Conditions similar to those which produce the cold waves of winter, but far less marked, prevail also in summer. The clearing northwest winds in the rear of a passing summer cyclonic storm, or after a well-developed wind-shift line thunderstorm, are pleasantly cool, dry, and refreshing, following, as they do, a spell of muggy and oppressive heat which has accompanied the southerly winds on the front of the low. These summer "cool waves" therefore give welcome relief during the hot months and are an important factor in making the climate of that season more agreeable and more healthful.

Factors Favorable to Cold Waves. Several factors combine to produce the severe cold spells of the eastern United States.

While the cold wave itself is directly due to the temporary pressure distribution, as will shortly be explained, the initial source of the cold is to be sought in the larger climatic conditions of the North American continent. During the long winter nights, under the prevailingly clear anticyclonic skies and in the dry air of the northern continental interior, active radiation from the lower atmosphere, both to ground and sky, reduces the temperature to very low readings. These fundamental conditions doubtless supply most of the cold, which is then imported to lower latitudes.[1] The permanent winter high pressure conditions over the northern portions of North America accelerate this flow of cold air, which is most active when a well-developed anticyclone follows the retreating cyclone. In addition, the original cold is reënforced and more or less effectively maintained by the active radiation which takes place in the dry clear air of the western quadrants of the cyclone and of the following anticyclone, as these move eastward across or along the northern border of the United States. This local reduction of temperature during the advance of the cold wave is especially effective when the ground is covered with snow.

Another factor of essential importance in the production of American cold waves is the frequency, intensity, and rapid progression of the winter storms. A further condition which makes the fall of temperature so marked is the presence of the warm ocean and Gulf waters to the south. Across these blow the warm southerly winds in advance of the low pressure areas, importing the high temperatures with which the succeeding cold is in such sharp contrast. There is, further, a series of topographic controls peculiar to North America. The Rocky Mountains constitute an effective barrier to the west. Hence cyclonic storms moving across the Great Plains and then eastward cannot readily supply their rear indraft from the west, and in place of that draw heavily on the reserves of colder air to the north. Further, this dry, cold, dense air finds itself moving with the general slope of the country down the Missis-

[1] See, for example, a discussion by Sir F. Stupart and the late Professor Cleveland Abbe on the origin of American cold waves in *M. W. R.*, Vol. 32 (1904), p. 113.

sippi Valley toward the Gulf of Mexico and eastward toward the Atlantic, easily underrunning the warmer, lighter air on the front of the storm along the wind-shift line. The absence of any transverse mountain ranges across the great central lowlands leaves an unobstructed path for the cold waves to invade the whole tier of states bordering on the Gulf of Mexico. The long stretch of the Appalachian Mountains, paralleling the Atlantic coast, is not sufficiently high or massive to constitute an effective barrier against the advance of cold waves from the interior, although it not infrequently furnishes some protection to the southern Atlantic coast states when severe cold waves prevail to the west of the mountains.

Some Economic Aspects of Cold Waves. A climatic phenomenon marked and far-reaching in its economic effects is the cold wave. Many and varied are the ways in which it affects man and his multitudinous activities and interests. When a cold wave is on the way, heating-plants, whether steam, electric, or natural gas, are prepared for an increased demand, and individual heating-systems and furnaces are run at full blast. Greenhouses are closed and kept at a higher temperature. Fire plugs and exposed water pipes are protected. Gasoline engines out of doors are drained. The water in automobile radiators is mixed with alcohol or some other non-freezing liquid. Railway companies arrange for more heat in their passenger cars; accelerate the movement of perishable goods and heat the cars containing them, or run these cars under cover for protection. The announcement of a cold wave is usually followed by hastened shipments of cold-storage eggs from the Western supply districts to the Eastern markets, in anticipation of a rise in prices. On the other hand, many goods are not shipped until the cold spell is over. Advertisements call attention to cold-weather goods. Coal and wood dealers prepare for sudden demands for fuel. The dredging of sand and gravel ceases. Iron ore ready for shipment is protected so that it shall not freeze. Ice companies watch the increasing thickness of the ice forming in their supply reservoirs and decide whether to cut at once or, if the cold is likely to be severe and prolonged, to wait for thicker ice. Philanthropic

organizations of all kinds prepare for sudden demands for fuel, food, and clothing on the part of the poor. In districts where outdoor crops are exposed to the cold and to frosts accompanying or closely following the advent of a cold wave, as in the citrus fruit orchards of southern California or the truck-gardens of the Gulf and southern Atlantic coasts, immediate preparations are made for adequate protection by means of thoroughly organized methods. In certain cases the crop may be saved by being gathered in advance of the arrival of the damaging cold. In these and in countless other ways cold waves play a distinct part in the lives of many millions of people in the United States.

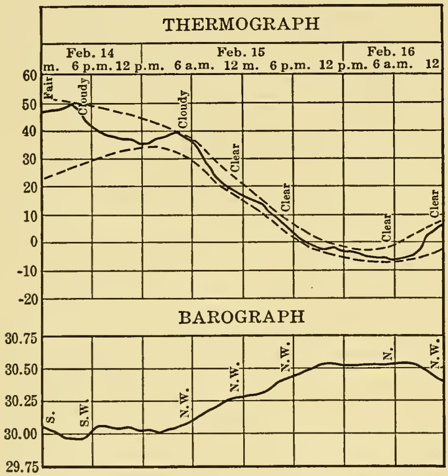

FIG. 134. February Cold Wave (February 14–16)

Instrumental Records of Cold Waves. A more vivid picture of the general characteristics of these sudden cold spells, which of course do not always meet the official definition of a cold wave, will be secured by a glance at the thermograph and barograph records obtained at a New England station. The temperature and pressure curves are supplemented by observations of the state of the sky and of wind direction. The conditions here represented are more or less typical for the whole area east of the Rocky Mountains, with modifications resulting from latitude and other controls. Fig. 134 illustrates a February cold wave. A maximum temperature of 50° F. is reached under the warm, damp, muggy southerly winds of a winter cyclone passing by on the north. With a shift of wind into the northwest as the wind-shift line passes the station, a rapid fall of temperature takes place from the early morning of one day (February 15), through noon, with practically no

trace of diurnal warming, although the sky is clear, to the early morning of the next day (February 16). The minimum (– 5°) comes under the clear skies and light winds at the crest of the high. The cyclonic control of temperature is strikingly brought out in the drop of the temperature belt (inclosed by the broken lines) from one side of the diagram to the other. The fall in temperature was over 50° in thirty-six hours, and

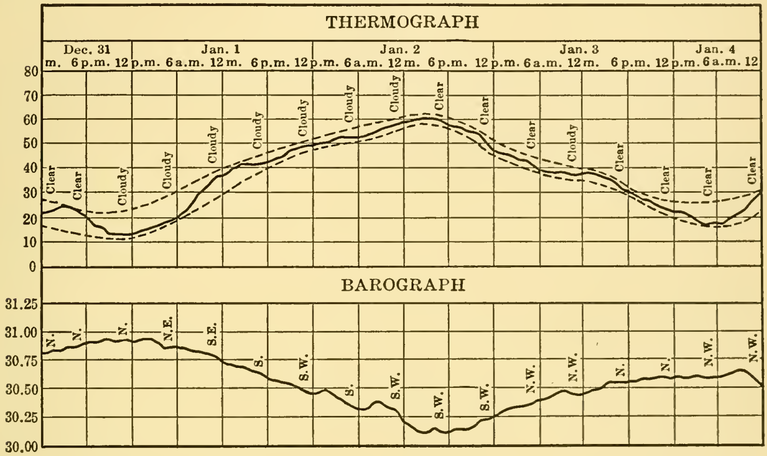

FIG. 135. Typical Winter Temperature Changes (December 31–January 4)

during all that time a strong biting northwest wind was blowing. Sudden temperature changes of this sort make it hard for persons who are not in robust health to endure the winters in the eastern United States. Fig. 135 is a good example of typical winter temperature changes under cyclonic and anticyclonic controls. A marked maximum of about 60° comes at the time of lowest pressure, under the control of the warm southwesterly winds and cloudy weather in association with the front of a winter cyclone passing by on the north (compare Fig. 134, February 14). The two minima come at the crest of the two high pressure areas. On January 1 the minimum is at the initial midnight, the maximum is at the final midnight, and the "diurnal range" is wholly cyclonic. On January 3 the maximum is at the initial midnight and the minimum at the

final midnight. This is exactly the opposite condition, but the diurnal range of temperature is again wholly cyclonic. On January 1 and 2 the normal diurnal curve, with the maximum in the early afternoon and the minimum in the early morning, has completely disappeared under the more powerful cyclonic control.

In Fig. 136 the rise of temperature in front of the approaching cyclone was only moderate (maximum under 40°), because of the blowing of rainy northeast winds (December 11) from the

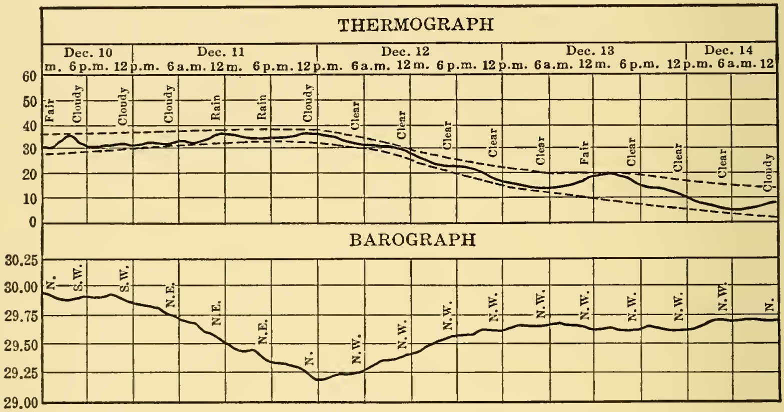

FIG. 136. Moderate December Cool Wave (December 10–14)

ocean. The fall of temperature under the northwest winds and clear skies of the succeeding anticyclone brought the thermometer down from between 35° and 40° to 5°, but rather slowly, as the pressure gradients were not steep, and the northwest winds were of moderate velocity. The cool wave carried the temperature belt down, the downward slope being only slightly interrupted by a weak diurnal maximum under solar control on the afternoon of December 13.

During the autumn the cyclonic control is less marked and the cold less severe. Fig. 137 illustrates a November cold spell. After a nocturnal maximum (November 19–20) of 40°, a fall in temperature beginning about 3 A.M. continues over noon (November 20) and until early morning of the following day (November 21). Such a fall of temperature over noon is one

of the characteristic signs of approaching winter. It shows the weakening solar and the increasing cyclonic control of the weather. The temperature belt is very narrow, showing slight diurnal ranges of temperature under the rain and the cloudy skies of November 19, and widens under the clear skies and light winds of the anticyclone (November 21). The minimum temperature (November 21) comes under the clear sky of the anticyclonic night, with very light northerly winds.

Another autumn cool wave is shown in Fig. 138. The fall in temperature comes in front of an approaching anticyclone; the temperature belt is lowered as a whole, although the sun is shining. The winds, however, are not strong enough and the imported cold not severe enough to extinguish the normal diurnal range (November 17), with its afternoon maximum.

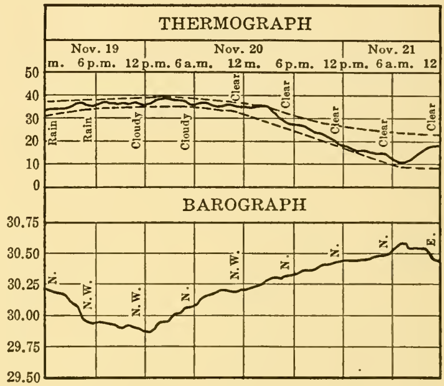

FIG. 137. November Cold Spell (November 19–21)

Weather Map Types Favorable for Cold Waves in the Eastern United States. Cold waves accompany well-developed areas of high pressure (cold wave anticyclones) coming from the Canadian west or northwest and following behind cyclonic areas moving eastward in advance of them. The cold over western Canada may be very intense, but it cannot advance far into the United States as a cold wave unless steep barometric gradients are present to make possible the draining off of the cold by the strong northerly and northwesterly winds blowing toward a cyclonic area to the south, southeast, or east. As conditions of this sort occur much more frequently over the Northern states than in the South, sudden marked temperature changes are most frequent in the North. The severity of a cold wave depends upon many factors. Among these are the

intensity of the cold in the cold wave high and the size and the degree of development of this high; the pressure gradients; the relative positions, the paths, and the rate of progression of the high and the low; the presence or absence of a snow cover; the amount of cloud; the latitude; the month, etc.

When a large number of cold wave weather maps are examined, it is seen at once that the number of possible combinations of high pressure areas and low pressure areas as to development, relative positions, paths, rate of progression, gradients, etc., is almost endless. A study of these type maps is of the utmost importance from the viewpoint of the forecaster. In the present discussion, however, which aims only to give the essential facts in their climatic rather than in their meteorological bearings, such details are quite unnecessary. The accompanying figures (Figs. 139–141) are broadly generalized, free-hand composite maps which are intended to illustrate, in a very general way, weather map types which are associated with the occurrence of cold waves in the eastern United States. The sketch maps here reproduced are not copies of any weather maps, and they are not to be taken as representing pressure conditions which must be fulfilled in order that cold waves may occur. They are merely intended to illustrate in a general way the kind of pressure distribution which favors a flow of cold air from western Canada into the eastern United States.

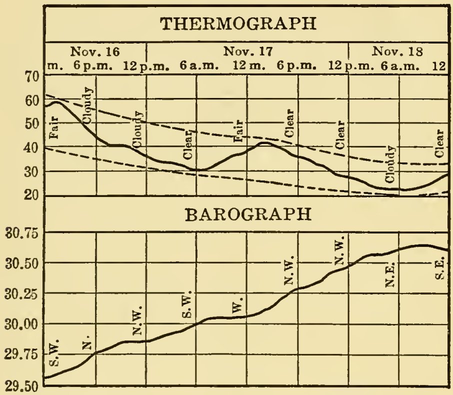

FIG. 138. Autumn Cool Wave (November 16–18)

Fig. 139 shows a pressure distribution favorable for the outpouring of a great volume of cold air from the high pressure area over western Canada, southward over the Great Plains and as far as the western Gulf region (Texas). Severe cold

waves reaching far to the south, into the states bordering on the Gulf of Mexico, occur when a well-developed cold wave high, accompanied by very low temperatures, thus appears in the Northwest, and when there is, at the same time, an energetic cyclonic depression over the Gulf or southern Atlantic coast section. As the low (Fig. 139) moves eastward and then northeastward along or more or less parallel to the Atlantic coast,

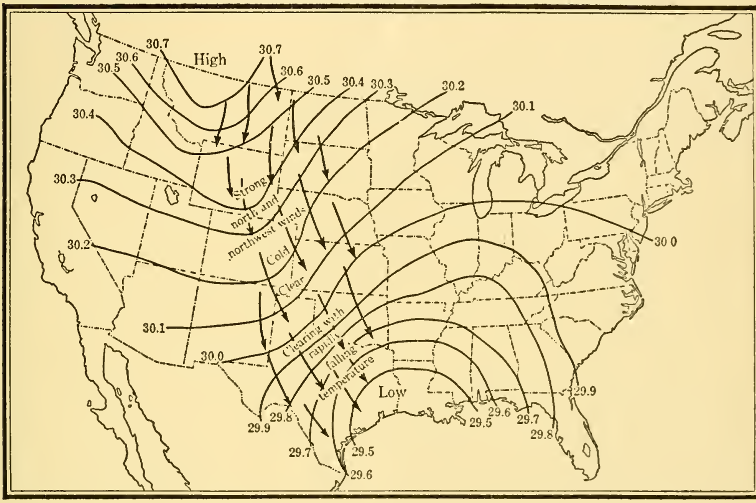

FIG. 139. Cold Wave Type Map: I

the cold wave sweeps eastward with the advance of the northwest winds, crossing the Mississippi Valley, overspreading the Southern states, and reaching the Atlantic coast. The high, with its low temperatures, normally moves southeastward across the Plains, gradually decreasing in energy, and with lessening cold as it later swings eastward across the Mississippi Valley to the central or southern Atlantic coast. Many variations may occur in these suggested conditions. If there is no well-defined depression in the South, the high is less likely to move in a southerly direction, and the area covered by the cold wave will be smaller and will not advance into such low latitudes. If the high is less emphatic or its cold less severe, or if the

gradients are less steep, the cold wave will be correspondingly modified, with diminished economic importance.

The situation broadly generalized in Fig. 140 is clearly not favorable for the transportation of severe cold into the Southern states. In this case the cyclonic depression moves eastward along the northern track (that is, across the Great Lakes and down the St. Lawrence valley), followed by a cold wave high

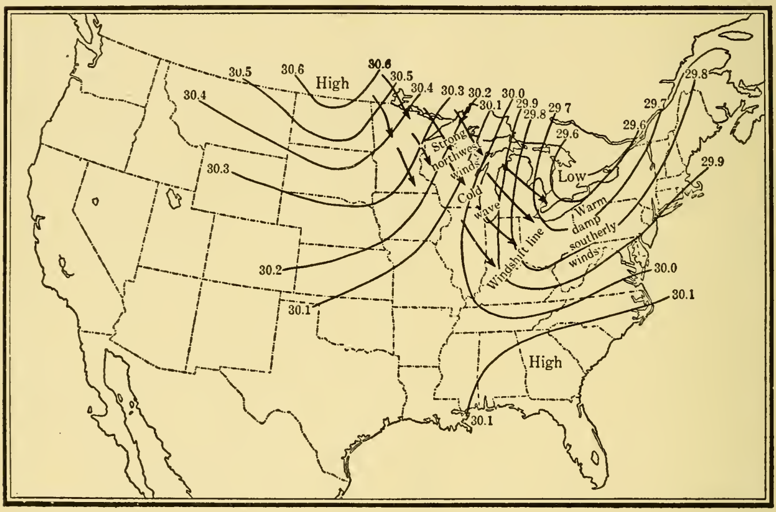

FIG. 140. Cold Wave Type Map: II

which follows more or less the same course. The cold wave under these conditions is limited to the northern and central sections of the eastern United States. Many variations of this general type occur. For example, the high may move southward from Canada over the Lakes, with a low in the northeast. Under these conditions the northeastern sections, including New England and the middle Atlantic states, are alone affected. In this portion of the country the cold wave is often preceded by an easterly snowstorm. Again, the smaller and weaker the depression and the farther north it is, the less severe and far-reaching is the cold wave. Certain large seasonal characteristics are controlled by the characteristics, the paths,

and the numbers of cyclones and anticyclones. Thus, when in a given winter more cyclonic depressions follow a southern route, being followed by well-developed cold wave highs coming from the northwest, there is a preponderance of cold northerly winds, and the winter is likely to be unusually cold. On the other hand, when more depressions follow the northern track, especially if the highs also come from farther south instead of

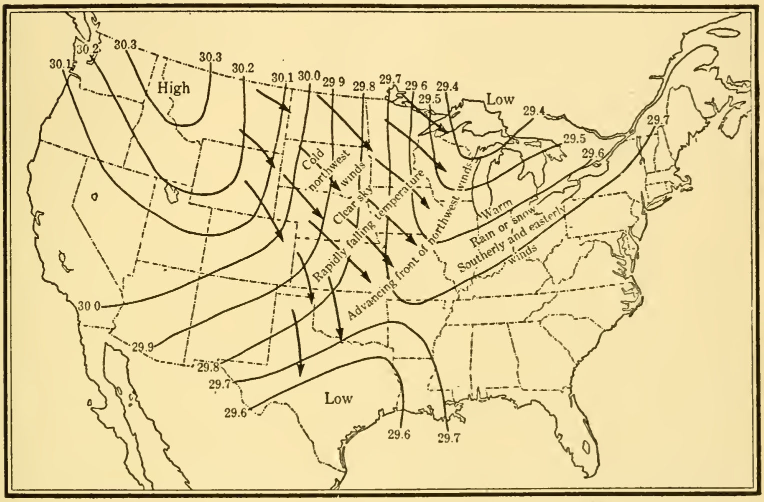

FIG. 141. Cold Wave Type Map: III

out of the Canadian northwest, there is a preponderance of warm southerly winds over the eastern United States, and the winter is likely to be milder than usual.

A weather map which is more or less of a combination of the types illustrated in Figs. 139 and 140 is shown in Fig. 141. Here a trough of low pressure extends from the Great Lakes southwest across the Mississippi Valley to the western Gulf. When the gradients are steep, with a well-marked high in the Far Northwest, a severe cold wave sweeps the eastern slope of the Rocky Mountains and follows the eastward movement of the low pressure system across the eastern United States.

As has been stated above, these three generalized type maps

are not to be taken literally, nor do they in any way show the great variety of conditions under which cold waves occur, and with which the forecaster has to deal. They are merely suggestions. But they may serve to make the matter clearer than would the description alone.

Tempering Effect of the Great Lakes. The open waters of the Great Lakes have a distinctly tempering influence on the bitterly cold winds of a cold wave. This effect extends well on into the spring, when the moderating influence is of considerable economic importance in the fruit districts of the lower peninsula of Michigan. This influence naturally decreases rapidly on going inland from Lake Michigan. The lee shores of Lakes Huron and Erie show similar effects. The number of cold waves is furthermore distinctly smaller at stations on the Lakes than at neighboring interior stations.[1]

Cold Waves of the Western United States. Reference has thus far been made only to the cold waves which sweep across that portion of the United States lying east of the Rocky Mountains. The cold wave chart (Fig. 132) shows that the rest of the country lying to the west of the mountains is also reached by sudden marked falls of temperature which meet the definition of cold waves. It will be observed that most of the Plateau area between the Rocky Mountains on the east and the Sierra Nevada-Cascade ranges on the west has cold waves of the same degree of intensity as those of the same latitudes to the east. On the north Pacific coast, on the other hand, cold wave conditions resemble those of latitudes 10° or so farther south on the eastern side of the Rocky Mountains, while California and southern Arizona have cold waves of the same degree as those of the Gulf and southernmost Atlantic coasts.

The great mass of the Rocky Mountains is an effective barrier to the westward flow of the cold air which is carried southward and eastward from the northern Great Plains. Low minimum temperatures occasionally occur over the Plateau under anticyclonic conditions which have drifted eastward from the Pacific coast, the cold air being drawn southward by northerly winds blowing toward a marked cyclonic disturbance.

[1] See Chapter V, pages 116–117.

Real cold waves are, however, not common. These are best developed when the high from the Pacific coast is intensified by high pressure over British Columbia.

The Pacific coast not only has a double mountain barrier on the east, against the cold of the interior, but is blown over most of the time by mild winds from the Pacific. Hence its cold waves are few in number and not severe. They are associated with northerly and northeasterly winds blowing out of a high over the northern Plateau or moving southward over the Pacific slope, with a low pressure system preceding it to the southward. Between the two, steep barometric gradients produce a flow of cold air which advances from north to south down the coast. The occasional frosts of California, which may be of serious consequence to the fruit industry, are the product of local radiation on clear, quiet anticyclonic nights.

American Cold Waves compared with those in Other Countries. Cool equatorward-blowing winds on the rear of extra-tropical cyclones are normal, but the peculiar winter conditions in North America, already referred to, combine to give these winds an unusual frequency and also an unusual intensity of cold. A brief comparison of these American cold waves with similar phenomena in other parts of the world is therefore instructive. This matter has been clearly summarized by Davis as follows:[1]

The winter cold wave of Europe is much less pronounced than with us, and comes from the northeast instead of from the northwest. . . . If a cyclonic center passes far enough south to draw the cold air after it from the low plateau of central France, the wind is called the *mistral* as it flows down the valley of the Rhone to the Mediterranean. . . . Central Europe never feels the excessive cold that is produced by the cold waves of the upper Mississippi Valley. . . . The name cold wave is not employed there, although it is perfectly applicable. Farther east, in Russia and Siberia, where the continental extension allows a more severe winter, the colder cyclonic wind is more like our cold wave. When of high velocity and raising a cloud of fine dry snow, it is called a *buran* or *purga*, corresponding to the *blizzard*. . . . The southern hemisphere has cool waves from the south in the rear of its cyclonic storms; but in the absence of large land areas in high latitudes, the fall of temperature

[1] W. M. Davis, "Elementary Meteorology" (1894), pp. 236–237.

is never as violent as with us; no strong cold waves occur there. The wind of this kind in the Argentine Republic is called a *pampero.* The *southerly burster* of New Zealand also seems to belong here.

Therefore it is not the nature of the phenomenon but its extraordinary development which gives the winter cold wave of the eastern United States its distinctive character.

The Texas Norther. In Texas and over the region of the Gulf of Mexico in general the cold (or cool) wave is called a norther. This wind has all the characteristics of the squall or wind-shift line conditions. It usually follows a general warm and cloudy or rainy spell with southerly winds. It comes as a rushing blast from the northwest or north and brings a sudden drop of temperature of maybe 25° or more in an hour, and over 50° or more in two or three hours in winter. Almost incredible stories are told of these temperature changes. Joseph Henry noted that "on one occasion recorded the temperature fell in the course of three hours from 75° F. to a degree sufficient to produce ice an inch thick."[1] The wild sweep of the norther over the open plains is dreaded by all who are outdoors exposed to its chilling fury. Shelter is sought when possible. Indoors, huge fires are quickly lighted, windows are closed, and the passing of the tempest is impatiently awaited. The sudden fall in temperature is especially disagreeable to human beings, and injurious to stock and to crops, because of the warmth and mugginess which precede it.

Northers are classed as "wet" and "dry." In the former the fall in temperature usually begins while showers are falling, and is accompanied by cold rain, perhaps turning into sleet and snow. In the latter the change to the cold clearing wind comes without any precipitation at all, or in advance of it. A wet norther is likely to freeze the rain on vegetation, covering fruits and flowers with an icy coating and causing serious injury. Stock left outdoors also suffer severely. Dark squall clouds rolling up from the north across the sky characteristically precede the norther. "The first appearance of the tempest," wrote Henry, "is a cloud in the north, which approaches the

[1] Joseph Henry, *Ann. Rept. Smithson. Instn. for 1871* (1873), p. 452.

observer sometimes with great and at other times with less velocity, and frequently passes over his head in a series of arches composed of dense clouds separated by lighter portions."[1]

Texas northers occur on steep barometric gradients produced by a well-marked anticyclone advancing over the Great Plains toward the Gulf of Mexico following a low-latitude cyclonic disturbance moving northeastward, with the wind-shift or squall-line characteristics strongly developed. Cold waves and northers are therefore simply, as Ferrel clearly stated, the usual trough phenomena of cyclones, where these are well marked. Or, as Blodget pointed out some decades earlier, in describing northers, they "are but the clear weather side of a revolving gale, like the northwester of the coast of the United States."[2] The prevailing winter pressure distribution over the great central region of North America is itself favorable to the prevalence of northerly and northwesterly winds. The dominant condition is one of north-south gradients from the cold northern interior to the warm Gulf of Mexico. When this condition is intensified by the presence of an especially marked cold wave anticyclone over the northern Plains or by a cyclonic storm originating over or crossing the western Gulf region, or by both combined, "the north winds may come down from the plains with great velocity, with a sharply defined head of cloud like a battering ram, replacing warm and stagnant air and causing a sharp and great fall of temperature. These are the well-known Texas 'northers.'"[3] These are, thus, simply temporarily exaggerated cases of the prevailing winter winds, similar in many ways to the *mistral* of Europe. The norther of Texas is therefore merely the local designation of cold wave phenomena already familiar through the preceding discussion, but owing to its occurrence in lower latitudes it is accompanied by less extreme cold. Severely destructive northers are infrequent. Sometimes they advance far southward along the eastern shores of the Gulf of Mexico and,

[1] Joseph Henry, loc. cit.

[2] Lorin Blodget, loc. cit.

[3] M. W. Harrington, "The Texas Monsoons," *Amer. Met. Journ.*, Vol. 11 (1894–1895), pp. 41–54.

occasionally crossing the Isthmus of Tehuantepec, blow onto the adjacent waters of the Pacific Ocean.

Well-marked northers usually do not last longer than a day or so. The wind then decreases in velocity, shifts to some southerly point, and a spell of fine and warm weather sets in— a transition as sudden, to quote an early writer, as that from "Labrador to Nicaragua." Overcoats and extra coverings are thrown aside, fires are allowed to go out, and the cold is forgotten.

Pressure conditions favorable to northers are not limited exclusively to winter, although they are most marked and most frequent then. The norther of spring and fall, coming at a time of prevailingly higher temperatures, is disagreeably chilly. In the summer, on the other hand, the northerly wind may furnish pleasant relief from the oppressive heat.

The Blizzard. The following description of a blizzard is taken from an article by C. A. Lounsberry:[1]

The sun at rising was hid behind a red mantle of clouds. The air was unusually moist. A gentle mist deposited moisture on every twig; the mist turned to rain; the rain to snow. About four inches of snow fell. The thermometer was in the vicinity of the freezing-point. About 9 P.M. the wind shifted to the northwest, and its velocity increased to about forty miles an hour. It turned cold, and each separate flake of snow became a particle of ice. . . . As the wind would lift fine dust and whirl it through the air, so this body of snow was lifted. To distinguish the form of a human being ten feet away was impossible. A barn, even, could not have been seen twenty feet in front of one. It was a mad, rushing combination of wind and snow which neither man nor beast could face. The snow found its way through every crack and crevice. Barns and stacks were literally covered by the drifting snow, and, when the storm was over, cattle fed from the tops of the stacks. My sheep huddled together in the sheds, and many of them were smothered. Persons lost upon the prairies were almost certain to meet with death, unless familiar with the nature of these storms. . . . I learned of many instances where persons were lost in trying to go from the house to the barn, and of other instances where cords were fastened to

[1] Reprinted from the *Northwest Magazine*, in *Amer. Met. Journ.*, Vol. 3 (1886–1887), pp. 112–115.

the house so that, if the barn should be missed, by holding onto the cord the house could be found again. During the blizzard the thermometer ranged from twenty above to ten below. After the storm it reached twenty-five below.

Such, in December, 1865, was a blizzard on the plains of North Dakota, and such is a blizzard in that same region today: a sharp, biting, irresistible cold wave gale, with rapidly falling temperature; with fine, dry, driven snow, and with cutting needle-like ice crystals. Its real home is on the northern Plains, but it also occurs, with diminishing severity and with lessened frequency, as one passes to greater distances from its northern habitat. In its typical development it is very destructive to cattle exposed to the full fury of its blast in the open plains, and many a farmer and cattleman has been lost in its blinding snow squalls and its bitter cold. All sense of direction is easily lost, and in the roaring of the gale the sound of the human voice is indistinguishable. "Caught in such a blast one runs the risk of suffocation, the action of the lungs being stopped by the swiftness as well as the intense cold of the wind, while the ice-dust, which penetrates the thickest clothing, is more choking than a summer dust-storm." The blizzard of January 12, 1888, in the Dakotas and neighboring states, came so suddenly after a spell of mild weather that between two and three hundred persons were reported to have lost their lives, being unable to find their way to shelter, and thousands of cattle perished.[1] Winds of over fifty miles an hour were recorded, with temperatures of $-20°$. The thermometer fell 50° in less than five hours at Helena, Montana, and at Crete, Nebraska, it fell 10° in five minutes.

The blizzard, like the cold wave, is a typical and distinctive American winter phenomenon: an occasional but fortunately not a frequent visitor to the sections where it has its home. Its most favorable opportunity occurs after a snowstorm, when the snow is still loose and soft, and on the steep gradients in the rear of the retreating low.[2] As in the typical cold wave,

[1] *M. W. R.*, Vol. 25 (1897), p. 15.

[2] F. J. Bavendick, "Blizzards and Chinooks of the North Dakota Plains," *M. W. R.*, Vol. 48 (1920), pp. 82–83.

the greatest degree of cold (it may be $-30°$ or $-40°$, or even lower) is not recorded until the gale has "blown itself out" under the clear skies and light winds or calms of the succeeding anticyclone. Yet the feeling of cold is far more intense during the gale.

There has been a good deal of discussion as to the origin and the first use of the word "blizzard."[1] C. F. Talman has given some attention to this matter. The origin of the word has been traced to the German *blitzartig* ("lightning-like"), and *blizzard* may first have been used by early German settlers on the northern Plains. At any rate, the term *blizzard* does not seem to have been used in a meteorological sense before about 1860. As is the case with any scientific term which has a definite meaning, blizzard should not be used indiscriminately to describe any particularly heavy snowstorm accompanied by high winds. Such a "popular" use of the word is quite general in the eastern United States in relation to a violent northeast snowstorm, and is unfortunate.[2] True blizzards are of rare occurrence in the latter region.

A memorable storm of this character occurred on March 11–14, 1888, which interrupted for several days telegraphic communication in southern New York, eastern Pennsylvania, New Jersey, and southern New England. Snowdrifts forty feet in depth were measured in places. The wind velocities averaged from twenty to twenty-five miles an hour for four days, and at times reached from fifty to seventy miles. Boston, Massachusetts, was so completely isolated that for a day or two communication with New York and other cities was by means of cable via England. The economic loss on land and sea ran up into many millions of dollars, and numbers of persons suffered severely from the intense cold, the icy gales, and the drifting snow.[3]

[1] See, for example, C. F. Talman, "Origin of the Word 'Blizzard,'" *M.W.R.*, Vol. 42 (1914), p. 692; see also Vol. 26 (1898), p. 562, and Vol. 48 (1920), p. 82.

[2] See also *Nature*, Vol. 97 (1916), pp. 261, 280, 301, and Sir Douglas Mawson's "The Home of the Blizzard," 1915.

[3] Everett Hayden, "The Great Storm off the Atlantic Coast of the United States, March 11–14, 1888," *Nautical Monographs No. 5, U.S. Hydrographic Office*, 1888; Winslow Upton, "The Storm of March 11–14, 1888," *Amer. Met. Journ.*, Vol. 5 (1888–1889), pp. 19–37; A. W. Greely, "American Weather," pp. 225–226.

CHAPTER XVII

HOT WAVES AND THE INDIAN SUMMER

INTRODUCTION · DEFINITION OF A HOT WAVE · GENERAL DESCRIPTION OF A HOT WAVE IN THE EASTERN UNITED STATES · HOT WAVE CHARACTERISTICS IN DIFFERENT SECTIONS OF THE EASTERN UNITED STATES · SOME ECONOMIC AND PHYSIOLOGICAL ASPECTS OF HOT WAVES · WEATHER MAP CONDITIONS FAVORABLE TO HOT WAVES IN THE EASTERN UNITED STATES · SOURCES OF HEAT IN A HOT WAVE · HOT WAVES IN OTHER PARTS OF THE UNITED STATES · DESCRIPTION OF INDIAN SUMMER · ORIGIN OF THE NAME · WHEN DOES INDIAN SUMMER COME? · INDIAN SUMMER TYPE WEATHER MAP · INDIAN SUMMER TYPE WEATHER MAPS OCCUR AT ALL SEASONS · SPECIAL PECULIARITIES OF THE INDIAN SUMMER TYPE IN THE AUTUMN MONTHS

Introduction. Spells of excessively hot weather, occurring at irregular intervals and lasting for varying periods of time, are characteristic of the summers of the central and eastern United States, especially of the great Mississippi lowland, of the Ohio valley region, and eastward even to the immediate Atlantic coast. Such periods of extreme heat, known as hot waves, warm waves, hot spells, or heated terms, are the antithesis of the cold waves of winter. Both are associated with certain well-defined pressure types. Both have many critical physiological and economic effects. Both are developed to a remarkable degree of intensity and frequency in the eastern United States.[1]

[1] For general discussions of hot waves see A. T. Burrows, "Hot Waves," *Yearbook U. S. Dept. of Agriculture for 1900* (1901), pp. 325–336, with charts; A. J. Henry, "Climatology of the United States," *U. S. Weather Bur. Bull. Q*, 1906; "Weather Forecasting in the United States," *U. S. Weather Bur. No. 583*, 1916 (page 290 and elsewhere, on hot waves). For discussions of the conditions and characteristics of individual hot waves see E. B. Garriott, "The Warm Waves of July and August, 1892," *M. W. R.*, Vol. 20 (1892), pp. 223–224; W. F. R. Phillips, "Sunstroke Weather of August, 1896," ibid., Vol. 24 (1896), pp. 409–413; idem, "Sunstroke in California and Arizona," ibid., pp. 454–456; F. H. Bigelow, "High Temperature Forecasts," ibid., Vol. 26 (1898), p. 292 (with Charts VIII–XII); A. J. Henry, "The Hot Weather of August, 1900," ibid., Vol. 28 (1900), pp. 333–336; idem, "Hot Spell of August, 1918," ibid., Vol. 46 (1918), pp. 361–363.

Definition of a Hot Wave. Any spell of uncomfortably hot weather in late spring, summer, or early autumn, lasting more than a day or so, is likely to be popularly spoken of as a hot wave. The longer the hot weather lasts, and the more excessive the heat, the more fully is it thought to deserve the name. There has been no official definition of a hot wave by the Weather Bureau, as in the case of a cold wave. According to Burrows a hot wave is a period of three or more consecutive days on which the maximum temperatures reach or exceed 90°.[1] This may perhaps serve well as a rigid limitation for meteorological use, but in the present discussion, which concerns the larger characteristics and relations of hot spells from their climatic viewpoint, no such clean-cut definition is necessary.

General Description of a Hot Wave in the Eastern United States. As a weak cyclonic depression moves slowly eastward across the northern tier of states, usually over the Great Lakes and down the St. Lawrence valley, the southerly and southwesterly winds that prevail in front of it, coming from warmer latitudes, bring very high temperatures, accompanied by high humidity and generally hazy skies. In the absence of an extended cloud cover, the normal diurnal variation of temperature, under the high and powerful summer sun, may carry the thermometer well up into the 90's, and even to 100° or over in the early afternoon hours. The night in a typical hot wave is likely to bring comparatively little relief, except in the mountains and on the coast. The importation of heat from warm southern latitudes continues with the northward drift of the air while the sun is below the horizon, and nocturnal radiation is reduced in the presence of the large amount of water vapor in the atmosphere.

In the typical cold wave the fall in temperature comes with great rapidity, as the wind shifts from southerly to westerly and northwesterly on the wind-shift line at the rear of the retreating cyclonic storm. The cold wind arrives as a sudden blast, at high velocity, and gradually dies down after a day or two. In the case of the American *sirocco,* as the hot wave

[1] A. T. Burrows, loc. cit.

might well be called after its well-known Italian counterpart, the southerly wind is apt to begin very gently, gradually increasing its velocity and bringing higher and higher temperatures as the gradients become steeper with the gradual approach of the depression, and finally, it may be, dying down again as the gradients weaken near its center. It is thus characteristic of hot waves that the maximum and the minimum temperatures may both become higher on the two or three or more successive days of these spells of warm weather.

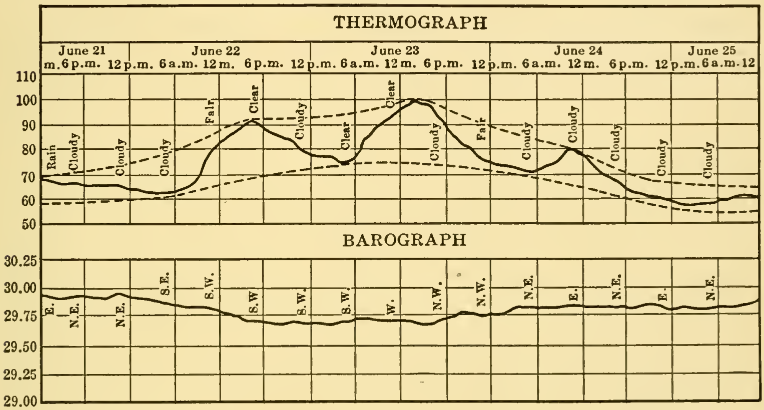

FIG. 142. Typical Instrumental Record during a Hot Wave in the Eastern United States

Fig. 142 is a reproduction of the thermograph and barograph records at a New England station during a short hot wave. It illustrates, within five days, conditions preceding, accompanying, and following a brief spell of very hot weather in that district. The record begins with moderate temperatures under cloudy skies and easterly winds coming from the Atlantic. The change of wind to southwest, with the slow eastward drift of an ill-defined summer cyclonic depression, brings a marked diurnal range of temperature under prevailingly fair or clear skies. The temperature belt (inclosed by broken lines) rises as a whole, under cyclonic control, to a high maximum (June 23), which is clearly the result of imported heat plus local warming

under sunshine. The high nocturnal temperatures (June 22–23) are characteristic. With a shift of wind to the northwest a general fall in temperature takes place. In the case of this particular occurrence, northeast and east winds quickly followed, bringing small diurnal ranges under cloudy skies, the temperatures falling as a whole. The low noon maximum on June 25 is due to these cool northeast winds and clouds. Cool spells of this kind near the coast afford welcome relief after the high temperatures of a preceding hot wave.

A sluggish movement, even at times an almost complete stagnation of the pressure conditions, is a feature of great importance in the summer weather types of the eastern United States, and accounts for the fact that hot waves sometimes last over the central portions of the country for two or even three weeks with little or no relief in temperature, or change in general weather conditions. Two or even more hot waves may come in succession with hardly a break between them. On the other hand, such hot spells may last two or three days only. They do not recur with any regularity, but in eastern sections there is often for a time a sort of sequence of summer weather types, consisting of a hot spell of two or more days, followed by a cooler period of about the same length, and then by another hot spell. Such a series depends upon a certain temporary regularity in the succession of summer cyclonic depressions drifting eastward across the northern tier of states. At least one severe hot wave may be expected every summer, and occasional summers have many of these extremely hot spells.

It is characteristic of a severe and prolonged hot wave which may cover as much as half the United States that it is accompanied by a protracted drought. Such precipitation as occurs is in the form of sporadic heat thundershowers, which are usually local, afford temporary relief only, and do not benefit large areas. The excessive heat combined with the drought constitutes the unfavorable feature for crops. The eastward movement of the cyclonic center eventually brings a shift of the wind from southerly and southwesterly to westerly and northwesterly, often accompanied by a series of severe wind-shift line thunderstorms. Then comes the summer cool wave, with

its brisk northwesterly winds, its bright blue skies, and the welcome relief of its refreshingly lower temperatures. At other times a general cyclonic rain may terminate the hot wave, followed by the shift of the wind to west and northwest.

Hot waves are to be looked for in the months from June to September. They are as a rule most frequent and most intense in July, but August and September do not lag far behind and are not infrequently characterized by hot waves of great intensity. Indeed, uncomfortably warm spells of a few days' duration, with southerly sirocco winds, occur as early as May, even in New England. Occasionally spells of extreme heat may occur with northwesterly winds when these have blown across extended districts that have been well warmed under clear skies.

Hot Wave Characteristics in Different Sections of the Eastern United States. As has been pointed out by Burrows, hot waves differ a good deal in different sections of the eastern United States. Over the Great Plains a hot wave not only brings very high maximum temperatures but is often accompanied by special local "hot winds" that are likely to cause serious damage to growing crops. The relative humidity over the Plains is less than in the East; the diurnal temperature range somewhat greater. Hence the oppressiveness of the high temperatures is lessened, and the nocturnal cooling gives a certain amount of relief during the night. East of the Plains, as a whole, the maximum temperatures are generally lower, but owing to the higher relative humidity the sensible temperatures are higher and the discomfort and suffering are greater. The hot nights, with minima often over 70°, are especially uncomfortable. Over the Mississippi and Ohio valleys, and eastward to the Atlantic coast, much suffering and illness result, especially in the crowded districts of the large cities, from the prolonged hot spells which occasionally prevail for a week or two at a time. The northeastern section of the United States, including the Great Lakes, has the advantage of being near the most-frequented paths of the weak cyclonic depressions of summer, and therefore of being reached by the cool northwesterly winds on the rear of these disturbances. Because of the small

size and slight development of most of these lows, the cool waves which follow them usually cannot advance far to the south, but are able to break the hot spell over the northern sections which are reached by the cool northwesterly winds. Along the Atlantic coast and the shores of the Great Lakes the cooling effect of the ocean and lake waters—whenever a cyclonic wind or a sea or lake breeze blows onshore—serves to break the monotony and continuity of many a hot wave which in interior districts may last for days without a break. Further, the northeastern section has the relief afforded by the occasional cloud-sheets of the weak cyclonic depressions which drift eastward across the Great Lakes and down the St. Lawrence valley, either with or without general rains (see Fig. 142).

The Southern states have a somewhat different relation to hot waves. They naturally have prevailingly higher summer temperatures. They are farther from the storm tracks. Yet when conditions are favorable they do not escape. Often, however, while warm southerly and southwesterly winds are giving hot wave conditions over the central and northern sections, northerly and northeasterly winds are blowing across Florida and the northern Gulf coast. Florida, with its winds coming from the Atlantic, may then have decidedly lower temperatures than states much farther north. Some years ago the writer was in northern New England during a severe July hot wave. Even in the New Hampshire mountains the maxima reached 90°, and the nights were uncomfortably warm. A correspondent in Florida wrote as follows of the weather conditions there:

> From all I could see in the newspapers, we had about the coolest place in the country down here. It is about 35 miles to the Atlantic Ocean and about 65 miles to the Gulf, and we have a delightful breeze most of the time. After supper we put on wraps and sit on our front porch, and are comfortable.

Some Economic and Physiological Aspects of Hot Waves. The combination of excessive heat and of a desiccating drought, if prolonged over several days, naturally results in serious damage to crops, which may extend over wide areas. If such a

hot wave comes at an especially critical period in the life of a staple crop, the financial loss may be much greater than that caused by a severe hurricane. It is not alone the accompanying drought which works the injury to growing plants. The baking effect of the high temperatures is in itself disastrous. Beneficial rains within a reasonable time may at least partly make good the injury caused by the drought, but the damage due to the heat may be permanent. Not only is the yield reduced in quantity, but the quality of the crop is inferior. A few hot spells, even if not greatly prolonged, may reduce the local yield in a summer of normal heat as much as 20 or 25 per cent. Fortunately, however, hot waves are not often equally severe over extended areas. Hence, while the damage in one state or one section may be considerable, other sections escape the worst effects.

Burrows has pointed out that the effects of hot waves as a general rule differ a good deal according to the time at which they come.[1] Thus June hot waves are naturally usually less frequent and less intense than those of midsummer and late summer. Furthermore, the normal type of rainfall distribution gives a June maximum over a large area of the great agricultural districts of the West. Hence many cereals, like corn, for example, are often benefited by high temperatures early in the summer. On the other hand, fruits which ripen in June are often seriously harmed. Crops maturing in the autumn are most liable to be permanently injured by hot waves in July and August. Not only is the heat likely to be greatest then, but the normal season of maximum rainfall has passed, and the scattering and sporadic thundershowers which bring most of such precipitation as occurs are quickly over, do not cool the air effectively or for long, and are soon followed by strong sunshine and active evaporation. Moreover, midsummer is a very critical time for many cereals. Indian corn may be withered by the excessive heat and its growth checked beyond the possibility of later recovery. In the South a severe hot wave at this season is liable to cause very serious injury to the cotton crop. Pasture grass may be so burned and withered as to be prac-

[1] A. T. Burrows, loc. cit.

tically useless for feed. September hot waves, as suggested by Burrows, are likely to drive some standing crops to maturity too quickly, but may on occasions help to ripen a backward crop.

An interesting train of economic effects accompanies any prolonged hot wave. A study of the effects associated with the heat and drought of July, 1901, was made by the writer some years ago, and illustrates the variety of economic aspects associated with this type of weather.[1] There was a marked increase in the demand for light-weight summer clothing of all kinds and for vacation supplies. The retail stores quickly sold out their stocks and sent in re-orders to the wholesalers. Thousands of people, suffering from the heat in the large Eastern cities, filled trains and steamers on their way to cooler summer resorts on the coast and in the mountains. Hotels and boarding-houses were crowded. The demand for ice and for all kinds of cooling summer beverages was tremendous. In order to save themselves the discomfort of shopping, customers sent in their orders by mail, and the large city stores were unable in many cases to keep up with their correspondence and had to engage extra clerks to handle it. The stock markets responded in a very striking way to the weather conditions. Not only were the prices of wheat, corn, and other cereals markedly affected, but so also were the stocks of the great cereal-carrying railroads. So sensitive to weather conditions are the stock markets that the prospect or the occurrence of even light showers in any portion of the hot wave area was immediately reflected in higher quotations. The lack of water and of pasturage, and the inevitable future high prices of corn, led Western cattlemen to ship their cattle to market in immense numbers. The result was that the prices of cattle on the hoof, of meat, and of hides dropped, and the great packing-houses were practically able to dictate their own terms. There was a greatly decreased market demand for meat, and an increased demand for fresh vegetables—so great that the supply was wholly inadequate, and in many cities the available stocks of canned vegetables

[1] R. DeC. Ward, "Some Economic Aspects of the Heat and Drought of July, 1901, in the United States," *Bull. Amer. Geogr. Soc.*, Vol. 33 (1901), pp. 338–347.

were sold out to meet the needs of customers. The settlement of a strike in some of the Pennsylvania steel mills was delayed because the operatives did not want to go back to work as long as the terrific heat lasted. In many cases manufacturing and industrial plants shut down, and large wholesale and retail concerns in the cities shortened the hours of work in order to give their employees a rest.

Such were some of the more obvious economic effects of one severe and prolonged hot spell. Similar conditions, varying with the locality, with the extent and severity of the heat, and with other factors, may be looked for in any well-marked hot wave.

The physiological effects of hot waves are none the less striking. The high maximum temperatures, the hot nights, and, in Eastern sections, the high relative humidity, at times combine to render the conditions almost insupportable. Heat prostrations, sunstroke, and other immediate and direct consequences of the excessive and uniform heat and humidity are common. The number of deaths, especially those of infants and young children from cholera infantum, may become appallingly large. A study by Dr. W. F. R. Phillips of the physiological effects of one prolonged and severe hot spell which occurred over two thirds of the eastern United States at the end of July and in the first part of August, 1896, is the only intensive investigation of this kind available.[1] Dr. Phillips found that during the three weeks ending August 22, 1896, there were 2036 known deaths directly due to sunstroke, and the list was doubtless far from complete. Probably more than 12,000 cases of varying degrees of severity actually occurred. The significant term *sunstroke weather* was suggested by Dr. Phillips as being appropriate for an especially fatal period during this long hot spell which he studied. As to the direct meteorological cause of sunstroke the author concludes that neither absolute nor relative humidity is as important as the value of the maximum temperature. He believes that sunstrokes do not occur until the temperature is well above that to which people are accustomed, regardless of other atmospheric conditions. Each locality "has for its native or acclimated inhabitant a

[1] W. F. R. Phillips, loc. cit., footnote 1, page 383.

special local sunstroke temperature or range of temperature." As a "working hypothesis" it is suggested that "the liability to sunstroke increases in proportion as the mean temperature of the day approaches the normal maximum temperature for that day."

Dr. Phillips's conclusions have not been unchallenged. His paper was discussed at a meeting of the American Climatological Association, where it was pointed out that one or two days of high maximum temperatures are less effective in causing sunstroke than continuously high temperatures both day and night for at least two days.[1] Henry has pointed out that serious discomfort is seldom felt unless the night temperature remains above 75°.[2] This value, however, probably varies slightly with the locality, being somewhat lower for New England (70°–72°). It has also been pointed out by others that the infrequency of sunstrokes in the Southwest, where the maximum and mean temperatures are much higher, militates against Dr. Phillips's views.

Weather Map Conditions Favorable to Hot Waves in the Eastern United States. The weather map types which produce hot waves are just the opposite of those which produce cold waves. The former generally bring the maximum heat on the northern and western outskirts of an anticyclone, whereas the cold wave area is to the south and east. Hot waves occur on barometric gradients sloping northward, the high pressure area being over the southeastern United States, and the depression in the north or northwest. In cold waves the high is in the northwest or north, and the low is to the south or east. The gradient system is thus essentially reversed in the two cases.

As in the case of cold waves, the weather maps which illustrate hot wave conditions differ a good deal from one another in details, and many type maps could be given as illustrations. The essential and fundamental condition may, however, be shown in a broadly generalized map (Fig. 143). This map is not a copy of any single daily weather map, but is drawn free-

[1] *Trans. Amer. Cli. Assoc.*, Vol. 13, pp. 234–237.

[2] A. J. Henry, *Annual Report of the Chief of the Weather Bureau for 1897* (1898), p. 264. Also "Climatology of the United States," pp. 39–45.

hand to represent a general pressure distribution which is favorable to the occurrence of hot wave conditions over the eastern United States. The characteristic features are an anti-cyclonic area over the Southeastern states and a moderate depression over the upper Missouri-Mississippi Valley region or the upper Lakes. For the production of a prolonged and intense hot wave this general distribution of pressure must

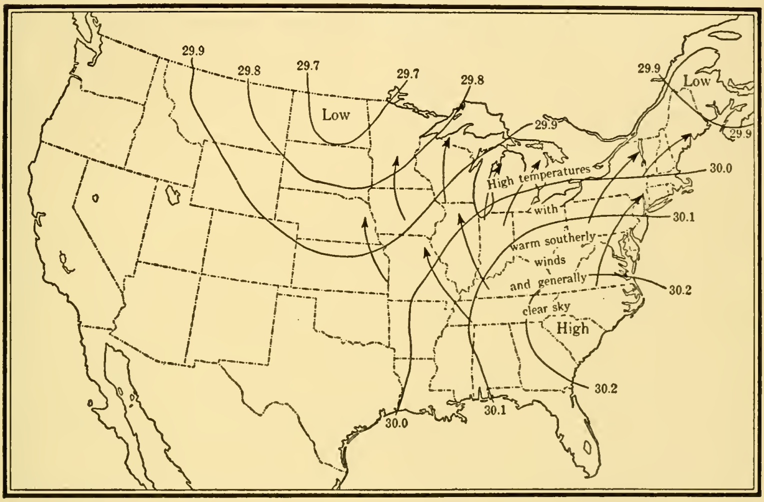

FIG. 143. Hot Wave Type Map for the Eastern United States

continue, without much change, for a good many days. In other words, there is a slackening or relative stagnation of the general circulation of the atmosphere. The regular eastward movement of low pressure areas along the northern border is somehow checked, and a general condition of low pressure persists for days over the Northwestern, Middle Western, or Northern states, instead of the more normal condition of an eastward drift of a series of cyclonic and anticyclonic areas, with shifting winds and showers or occasional thunderstorms. The southeastern high pressure area, which is really the western margin of the great tropical high pressure belt of the North Atlantic Ocean, also persists with essentially no inter-

ruption or change for days, and seems to act as a barrier to the eastward movement of the cyclonic depression to the north of it. In this type of map a great flow of warm southerly winds covers the interior valleys and most of the Atlantic coast. With the slow eastward drifting of a low pressure area across the Lakes and thence down the St. Lawrence valley, conditions are favorable for the occurrence of a hot wave well into the Northeastern states and along the Atlantic coast as far as New England. On the other hand, the persistence of the low pressure condition in the Northwest favors the occurrence of a hot wave over all the great central valleys. With the eastward movement of the northern cyclonic depression and the disintegration of the southern anticyclone, the hot wave conditions come to an end.

Sources of Heat in a Hot Wave. The excessive heat of a hot wave is due to a combination of several factors. Among these are (1) the importation of air from southern latitudes; (2) the effective cumulative warming, to a greater height than usual, of the earth's surface and of the lower layers of the atmosphere under the strong summer sun unhindered by any general cloud cover, the diurnal heating being in excess of the cooling by nocturnal radiation; (3) a certain amount of dynamic heating of the descending air under the anticyclone. The cumulative effect of these various contributing causes, when continued for several days, is such that, as Henry has put it, a greater impulse than usual is necessary to put an end to the existing conditions and bring about cooler weather.

Hot Waves in Other Parts of the United States. In the preceding discussion reference has been made only to the hot waves of the broad region east of the Rocky Mountains. These are the most extended and most striking phenomena of their kind in the United States. Yet hot spells are by no means unknown elsewhere, although the conditions of their occurrence and their characteristics are different. It often happens that while a severe and prolonged hot wave is prevailing over the eastern section of the country, other sections, such as the Plateau or the Pacific coast, are abnormally cool. The western mountain and plateau districts have the advantage of active

nocturnal radiation in the dry air and under the clear skies of those elevated areas, so that even when the days are very hot the nights are characteristically cool. Long periods of high temperature are, however, normal summer conditions over the less elevated portions of the Plateau Province, and the summer "heat island" of North America centers over the southern portion of this district. The Pacific coast is exempt from the severe and prolonged hot waves which characterize the eastern United States; but occasional short spells of uncomfortable heat occur even on the coast, although the prevalence of on-shore winds from the Pacific most of the time insures this coastal belt unusually cool and temperate summers. The interior valley of California, however, which is well shut off from ocean influences throughout nearly its whole extent, has very hot and dry summers, notably so in the south. The conditions are especially uncomfortable when an occasional hot north wind blows. Locally this wind is not only unusually hot, but also dry and dust-laden and becomes very disagreeable and trying. This California norther is discussed in Chapter XVIII.

Description of Indian Summer.[1] No type of American weather has been accorded such widespread and unstinted praise as has the "Indian summer." Poets, masters of literature, historians, travelers, meteorologists, and even the daily newspapers have united in their enthusiastic descriptions of its charms. It may not be inappropriate to include here two of these many printed accounts for the reason that they were written by men who are among the most widely known American writers of the past generation. In his "History of the Conspiracy of Pontiac," Francis Parkman wrote thus:[2]

> ... then succeeded that gentler season which bears among us the name of the Indian summer; when a light haze rests upon the moving landscape, and the many-colored woods seem wrapped in the thin drapery of a veil; when the air is mild and calm as that of early June, and at evening the sun goes down amid a warm, voluptuous beauty, that may well outrival the softest tints of Italy.

[1] The following paragraphs on Indian summer were originally printed as an article in *Proc. Amer. Phil. Soc.*, Vol. 62, No. 2 (1923), pp. 48–56, and are here reprinted by permission.

[2] Francis Parkman, "History of the Conspiracy of Pontiac" (1851), p. 404.

But through all the still and breathless afternoon, the leaves have fallen fast in the woods, like flakes of snow, and everything betokens that the last melancholy change is at hand.

With his inimitable charm Dr. Oliver Wendell Holmes described the Indian summer of his beloved New England in the following delightful passage:[1]

In October, or early in November, after the "equinoctial" storms, comes the Indian summer. It is the time to be in the woods or on the seashore—a sweet season that should be given to lonely walks, to stumbling about in old churchyards, plucking on the way the aromatic silvery herb everlasting, and smelling at its dry flower until it etherizes the soul into aimless reveries outside of space and time. There is little need of trying to paint the still, warm, misty, dreamy Indian summer in words; there are many states that have no articulate vocabulary and are only to be reproduced in music, and the mood this season produces is of that nature. By and by, when the white man is thoroughly Indianized (if he can bear the process), some native Haydn will perhaps turn the Indian summer into the loveliest *andante* of the new "Creation."

These quotations indicate, in poetic and expressive terms, the characteristics of the Indian summer: the calm, sunny days; the dry, mild, and genial atmosphere; the smoky haze which lends to the distant view a soft, indistinct, impressionistic tone and paints the sunset a glorious but subdued red; the wonderful coloring of the autumnal foliage; the welcome return, for a short space, of summer warmth following the first frosty nights and cool days of advancing winter.

Origin of the Name. Much interest centers in the origin and meaning of the term "Indian summer," and diligent search has been made by scholars of the literature bearing upon this question. Among these Albert Matthews has made the most exhaustive study of the historical usage of the name, as well as a critical examination of the various explanations which have been given of its original meaning.[2] The first use of the name

[1] Oliver Wendell Holmes, "Pages from an Old Volume of Life" (1891), pp. 165–166.

[2] Albert Matthews, "The Term Indian Summer," *M. W. R.*, Vol. 30 (1902), pp. 19–28, 69–79. (This paper contains a very complete bibliography and many quotations from the original sources.) See also Josiah Morrow, "Indian Summer," ibid., Vol. 39 (1911), pp. 469–470.

was for some twenty years attributed by Matthews to Major Ebenezer Denny, who mentioned it in his "Journal" kept at Le Bœuf, near the present city of Erie, Pennsylvania, October 13, 1794. An earlier case has, however, since been reported by Matthews. This appears in a letter dated "German-flats, 17 Janvier, 1778." In this Crèvecœur gives a "Description d'une Chute de Neige, dans le Pays de Mohawks, sous le rapport qui interesse le Cultivateur Américain."[1] Speaking of heavy autumn rains, followed by severe frost, the writer says:[2]

> Sometimes the rain is followed by an interval of calm and warmth which is called the Indian summer (l'été sauvage); its characteristics are a tranquil atmosphere and general smokiness. Up to this epoch the approaches of winter are doubtful; it arrives about the middle of November, although snows and brief freezes often occur long before that date.

Various suggestions have been made to explain the use of the word "Indian" in connection with Indian summer. One is that the Indians selected this time of the year as their season for hunting, "to which it is highly conducive," as an unknown writer remarked, "not only on account of the plenty and perfection of the game, but also in consequence of the haziness or obscurity of the air, which favors a near, and unsuspected approach, to the object of pursuit."[3] Another suggestion is that the characteristic smoky haze in the air at this season was due to the fact that the Indians then set fire to the prairie grass, woods, and underbrush. With reference to these views Matthews observes that the Indians also hunted and set fires at other times of the year. Other explanations are that the Indians made use of the dry, clear weather for attacking the whites again before winter set in, that this was the season for the Indian harvest, that the term was derived from the prevalence of southwesterly winds regarded by the Indians

[1] Lettres d'un Cultivateur Américain . . . depuis l'Année 1770 jusqu'en 1786, par M. St. John de Crèvecœur, Traduites de l'Anglais (Paris, 1787), Vol. I, p. 294.

[2] Translation by Dr. Cleveland Abbe, Jr. See note by Albert Matthews in *M. W. R.*, Vol. 39 (1911), p. 469.

[3] "Essay on the Indian Summer, read at a Meeting of the Maryland Academy of Sciences by One of its Members, Baltimore, December 16, 1833," *Amer. Journ. Sci.*, Vol. 27 (1835), pp. 140–147.

as sent by special favor from a beneficent deity thought to reside in the Southwest, and that the unreliability of Indian summer weather suggested the deceitfulness of the Indians. After a critical examination of these different theories Matthews concludes: "We shall therefore be obliged to suspend judgment with respect to the origin of the name of the Indian summer season until fresh evidence as to the early history of the term is produced. . . . It is possible that the name will some day be traced to an Indian myth or legend."[1]

G. L. Kittredge has also investigated the origin of the term.[2] This authority thinks it far-fetched to attribute the use of the word "Indian" to haziness of the sky from the brush and forest fires kindled by the Indians in the autumn, and believes it "far more reasonable" to think that reference was made to the "proverbial deceitfulness and treachery of the natives" or to their "equally proverbial instability." He also thinks it "conceivable that Indian summer was at first equivalent (among the earliest English immigrants) to 'fools' summer.' If so, we seem to have a parallel to the 'Old Women's Summer' of the Germans. . . ."[3] The conclusion, however, is that the "origin of the term is a mystery."

A wholly different origin of "Indian summer" has been suggested by H. E. Ware, who indicates that Indian in this connection may have referred to a nautical use in the British Indian seas.[4] Under the Regulations of the British Board of Trade one of the load-lines on ships bears the initial letters "I. S.," this indicating the maximum depth to which vessels

[1] Albert Matthews, loc. cit. in footnote 2, page 396.

[2] G. L. Kittredge, "The Old Farmer and His Almanack" (Cambridge, Massachusetts), 1920, pp. 191–207.

[3] The term *Altweibersommer* is applied to similar spells of autumn weather in Germany.

[4] H. E. Ware, "Notes on the Term 'Indian Summer,'" *Publ. Colonial Soc. Mass.* (Boston, Massachusetts), Vol. 18 (1917), pp. 123–130 (the author cites a poem by Philip Freneau, dated 1815, as the first appearance of the name in poetry, and quotes Mrs. Sigourney's poem on the same subject, written before but published in 1849). See also C. F. Talman, "Indian Summer," *M.W.R.*, Vol. 43 (1915), pp. 44–45. W. G. Reed, "Indian Summer and Plimsoll's Mark," ibid., Vol. 44 (1916), p. 575 (the latter paper gives a photograph (Fig. 2, opposite page 575) of the load-line marks on the bow of the British S. S. *Dramatist* of Liverpool, taken at San Pedro, California, on October 14, 1916).

can be loaded for voyages during the "Indian summer," which means the fine-weather season in the Indian seas. It is possible, though unlikely, that the Indian summer of the eastern United States was thus named by travelers or seamen who saw in it some resemblance to the fine weather during the northeast monsoon of India.

Whatever may have been its origin, the term "Indian summer" was evidently first used in the eastern United States, probably in New England, and spread thence westward across the Mississippi Valley, southward along the Atlantic coast, and northward into Canada. It appears, however, today to be most familiarly known and most commonly employed in the northeastern portion of the United States.

When does Indian Summer come? Opinions have differed a good deal both as to the time of occurrence and also as to the duration of Indian summer. This fact becomes obvious to anyone who examines the literature on this subject or who questions persons with whom he comes in contact. The term has been most commonly used for warm, dry, hazy spells in the autumn months, but it has also been applied to warm spells in December and even in January. Some writers have referred to it as peculiar to New England; others have stated that it occurs widely over most of the United States, even on the Pacific coast. Others, among the older writers, held the view that the Indian summer was more marked in their time than formerly; another group maintained that it was less marked. One unknown author, who held that "the Indian summer appears usually in the month of November," went so far as to observe that a similar type of weather "is by no means uncommon in the month of October and is frequently mistaken for the true Indian summer by persons unacquainted with the proper period of its accession." Blodget maintained that it is held certain that one such period, of some days' duration, will occur in October of every year.[1] In spite of these divergent views it is today distinctly the trend of popular opinion that Indian summer comes in the autumn, some time in October or November, after the first severe frost, and that its length is

[1] Lorin Blodget, "Climatology of the United States" (1857), p. 233.

indefinite, varying in different years.[1] Sometimes, however, there is no Indian summer at all; in other years two or three spells of warm weather all seem to merit the name.

A collection of daily weather maps for autumn days of marked Indian summer characteristics has been made during a number of years past. On the basis of these maps a very much generalized sketch map was drawn, free-hand, showing in broad outline the general distribution of pressure, winds, and weather prevailing during these Indian summer periods (Fig. 144). This map is not a composite, traced off from a large number of maps and then generalized, nor does it represent any individual map.

Indian Summer Type Weather Map. The conditions here shown are typical of most Indian summer weather maps over the eastern United States. A dominant anticyclone is central over the southern Atlantic coast. A moderate depression is over the Lakes. Generally clear weather prevails, with some cloudiness and perhaps scattered local showers over the upper Lakes region. There are gentle southerly to southwesterly winds or calms, hazy skies, and temperatures above the seasonal average, with fairly well-marked diurnal ranges, giving cool, pleasantly refreshing nights. Many modifications of the type here shown may occur. Thus the high pressure area may be somewhat farther north or west, or the low may be better defined and over the northern Plains. In the latter case conditions favorable to warm, fair weather prevail west of the Mississippi Valley. Again, the depression may be farther northeast, toward the Gulf of St. Lawrence. These variations in pressure distribution bring about changes in the area covered by, and in the local characteristics of, the Indian summer

[1] See, for example, Cleveland Abbe, "The Time and Duration of the Indian Summer at Washington," *M. W. R.*, Vol. 33 (1905), p. 489. Thoreau, in notes on weather conditions at Concord, Massachusetts, from 1851 to 1860, recorded the occurrence of Indian summer weather on dates ranging from September 27 to December 13. In the past twenty-five years, at frequent intervals during the autumn months, the writer has questioned his students regarding their own impressions on this subject and finds that their views are the same as the majority opinion above stated. In some years, when more than one spell of Indian summer weather occurred, there has been considerable doubt as to which one of these was *the* Indian summer, the preference being to apply that term to the longest and most marked of these spells.

type; but as long as the general situation here outlined continues, the same weather conditions will last. It is quite characteristic of Indian summer spells that they usually persist for several days, the depressions being poorly defined and moving slowly eastward, while the anticyclone maintains its position without much change. Such a spell of weather usually breaks

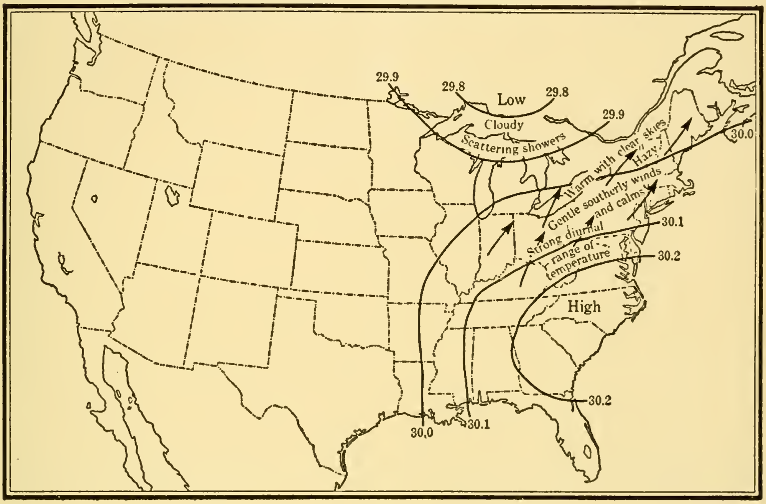

FIG. 144. Indian Summer Type Map

up with a general, often a cold, rain, accompanying a well-marked cyclonic storm crossing the eastern United States.

Indian Summer Type Weather Maps occur at All Seasons. The popular impression regarding Indian summer, that it comes after a severe frost in autumn, is associated with the idea that the special type of weather map which gives rise to this well-known spell occurs only in the autumn. This is not the case. Such general pressure conditions as those broadly generalized in the accompanying map may occur in any month, although the weather which accompanies them and the intensity and movements of the controlling high pressure and low pressure areas vary with the seasons. For a good many years the writer has collected Indian summer type weather maps whenever such

were found. The charts cover every month in the year. In other words, spells of fine weather, with temperatures above the average, hazy skies, and gentle southerly winds are likely to come at any time. In winter, when there is snow on the ground, such a condition brings a thaw. The warm damp winds, chilled as they blow over the cold surface, may even become foggy or cloudy. If the ground is bare, the sky is clear or fair, and we have a spell of "springlike" weather. An Indian summer type about December 25 gives a "green Christmas"; in January, a "January thaw"; in March, April, and May, a spring "hot day"; in summer, a hot wave.

Special Peculiarities of the Indian Summer Type in the Autumn Months. Is there, then, any special peculiarity about this type of weather when it occurs in autumn and is generally termed the true Indian summer? The answer to this question is probably to be found in the interaction of a number of factors. In the fall of the year there is characteristically something in the nature of a stagnation, or slackening, in the general movements of the atmosphere. The anticyclone over the south Atlantic slope often persists for several days; while the usual procession of cyclonic depressions passing over the Lakes and down the St. Lawrence valley is interrupted, and weak, slow-moving, and often poorly developed low pressure areas appear instead. The barometric gradients are apt to be weak. Autumn is a transition season. The cyclonic activity of the colder months has not yet set in. The thunderstorm activity of the summer has passed. There is a pause, as it were, before the turbulence of the winter begins in earnest; and a period, or several periods, of warm, quiet weather may set in. As an early writer poetically expressed it, "The air is perfectly quiescent and all is stillness, as if Nature, after her exertions during the summer, were now at rest."[1] Over much of the country, especially in the east and southeast, the autumn months are a season of minimum, or at least of a small rainfall. Thus dry spells are likely to be especially frequent then. This is, furthermore, the time when forest, brush, and grass fires are common, accidentally started by a

[1] John Bradbury (1817), quoted by Albert Matthews, loc. cit. in footnote 2, page 396.

careless hunter or tramper or by the sparks from a locomotive. It is also a time when dead leaves and other garden rubbish are apt to be burned, in the final clearing up of many gardens at the close of the summer. Thus the more or less calm and stagnant atmosphere often becomes smoky. It is this smoke, combined with the haze caused by the condensation of water vapor in the warm southerly air currents and with the dust derived from the minute particles of the dry leaves, that gives the softness and impressionistic quality to the distant view and adds so much to the beauty of the typical American Indian summer. In addition, the long nights and the small vertical temperature gradient of autumn contribute to the production of quiet atmospheric conditions at that time of year and therefore to the accumulation of smoke and dust in the lower air. And, finally, there is the satisfaction that comes from experiencing days of real warmth after the first chill of autumn frosts — a reminder of the summer which has passed; a final breathing spell when we may once more revel in the full enjoyment of outdoors before the storms and cold of winter change the aspect of nature.[1]

[1] For additional references see Lyman Foot, "Remarks on Indian Summer," *Amer. Journ. Sci.*, Vol. 30 (1836), pp. 8–15; J. E. Willet, "Indian Summer," ibid., Vol. 44 (1867), pp. 340–347; W. M. Wilson, "Indian Summer," *M. W. R.*, Vol. 30 (1902), pp. 440–442; R. M. Brown, "Indian Summer," *Journ. Geogr.*, Vol. 8 (1909), pp. 25–31.

CHAPTER XVIII

HOT WINDS AND CHINOOK WINDS

DESCRIPTION OF HOT WINDS · ECONOMIC AND PHYSIOLOGICAL ASPECTS OF HOT WINDS · WEATHER MAP CONDITIONS FAVORABLE FOR HOT WINDS · CAUSE OF THE EXCESSIVE HEAT AND DRYNESS OF HOT WINDS · DESCRIPTION OF A CHINOOK WIND · GENERAL CHARACTERISTICS OF CHINOOK WINDS · ORIGIN AND USE OF THE NAME "CHINOOK" · WEATHER MAP TYPES FAVORABLE FOR THE OCCURRENCE OF CHINOOK WINDS · ORIGIN OF THE WARMTH AND DRYNESS OF THE CHINOOK WIND · ECONOMIC ASPECTS OF CHINOOK WINDS · WINDS OF CHINOOK CHARACTER IN CALIFORNIA: NORTHER AND SANTA ANA

Description of Hot Winds.[1] Reference has been made above to the occasional occurrence, during summer hot waves on the Great Plains, of so-called "hot winds." These are a definite feature of the climate of the eastern slope of the Rocky Mountains. They are a special local development of abnormally hot currents of air within a general flow of hot winds covering a large area. Popularly the expression "hot winds of the Plains" has come into use because of the occurrence of these local superheated currents chiefly over the Great Plains region, between the eastern Rocky Mountain foothills and the Mississippi River and mostly between latitudes 34° and 45° N. They are especially well known in the drier, western parts of

[1] The following references are the most important discussions of hot winds. Most of what here follows is based upon them. G. E. Curtis, "The Hot Winds of the Plains," *7th Biennial Rept. Kansas State Board of Agric.*, December, 1890 (contains descriptions of numerous occurrences, and includes weather maps showing hot wave conditions; period covered, 1880–1889); I. M. Cline, "Hot Winds in Texas, May 29 and 30, 1892," *Amer. Met. Journ.*, Vol. 9 (1892–1893), pp. 437–443; idem, "Summer Hot Winds on the Great Plains," *Bull. Phil. Soc. Wash.*, Vol. 12 (January, 1894), pp. 309–348 (collection of all cases recorded since 1870, illustrated by three typical hot wind maps; also discussion of causes; reprinted in part in *Amer. Met. Journ.*, Vol. 11 (1893–1894), pp. 175–176); A. J. Henry, "Climatology of the United States," *U. S. Weather Bur. Bull. Q* (1906), pp. 56–57. Numerous cases of individual occurrences of hot winds are described in the *Monthly Weather Review.*

the Plains. In much less marked development they have been reported as far east as Illinois, Wisconsin, Indiana, Michigan, and Ohio. The hot winds of Kansas and Texas have been most often described and most thoroughly observed and studied.

The chief characteristics of these winds are their intense heat and their extreme dryness. They come in narrow bands of excessively hot winds, ranging from perhaps one hundred feet to a half mile or so in width, in a general hot spell, with intermediate belts varying from a few yards to a few miles in width of somewhat less terrific heat between them. Hot winds usually last only a few hours, but may recur in rapid succession in the same general locality. They have a habit of coming in groups, thus perhaps affecting a territory of a few hundred acres. At times an extended development of hot wind conditions may bring them here and there over a much larger area, embracing most of a state, or even portions of two or three states. Their direction is usually southwesterly or southerly, but occasionally they blow from the southeast and even from the north. Their velocity varies from a gentle breeze to a gale, and they are diurnal in their occurrence, usually dying down toward sunset. The winds may continue to blow throughout the night, but the temperature is then generally lower and more endurable. Very hot nights are, however, by no means unknown. It has been reported in one case that people woke up in the night and thought their houses were on fire. July and August bring most of the hot winds, but they also occur before June and into September.

The dry withering heat in a true hot wind has been compared by many observers to the blast from a hot furnace. Temperatures of 100° to 110°, and even higher, are recorded in the shade. On one occasion the temperature rose 7° in ten minutes on the setting in of a hot wind. The Weather Bureau observer at Leavenworth, Kansas, reported as follows during a hot wind:[1]

At 1 P.M. a very hot and extremely dry wind set in from the southwest, feeling as a hot blast from a furnace. It caused the thermometer to rise rapidly, attaining a maximum of 101° at 4 P.M.,

[1] Quoted by A. J. Henry, loc. cit.

and the humidity dropped suddenly to 17 per cent. This hot wind continued until sundown. It withered and almost burned vegetation and caused a total suspension of outdoor labor during the afternoon.

Another observer, at Lawrence, Kansas, reported that the air was excessively dry. The relative humidity fell to 7 per cent. The nights following three days of hot winds were, however, "comparatively cool" (minima 65°–66°). A brief summary of the official meteorological record during the hot winds in eastern Kansas on September 12, 1882, is given by Henry.[1] Although ordinary psychrometer readings are by no means accurate, especially when the air is excessively dry, there is no doubt that the percentage of relative humidity falls to 20 per cent or even less.

Economic and Physiological Aspects of Hot Winds. The excessive heat and dryness of these hot winds, which usually blow with considerable velocity, make them very injurious to all crops. They are veritable scourges, but fortunately do not occur often in their greatest severity. Not only is moisture evaporated from the soil, but growing vegetation is literally dried out as it stands. If the hot winds happen to come at a critical period in the growth of a crop, they may cause heavy damage within a few hours. In one case of recurring hot winds in Kansas some years ago, over 10,000,000 bushels of corn were ruined, and the crop was reduced by 10,000,000 more. Vegetation withers; leaves crumble to dust at the touch; corn, wheat, and other cereals look as if they had been scorched by fire; apples are described as being baked while hanging on the trees. So destructive are these winds that during the summer, when the harvest is in a critical stage, reports of hot winds in the West are at once reflected in the future price of wheat, corn, and other crops on the exchanges. The moister the soil, as a rule, the less destructive is the hot wind. Therefore any method of conserving soil moisture tends to lessen the damage. Further, as evaporation depends largely upon the velocity of the wind, there is some protection in wind-breaks, which decrease the wind movement.

[1] "Climatology of the United States," *U. S. Weather Bur. Bull. Q* (1906), pp. 56–57.

A case is on record, on the Southern Pacific Railroad in Texas, when during severe hot winds the rails expanded to such an extent that they were "sprung," and traffic had to be suspended until the rails were shortened and replaced.

If hot wind conditions continue for several days, great suffering to human beings and to animals in the intensely hot, dry air results. The skin becomes dry and parched. One observer, in Texas, reported of the hot winds of May 29–30, 1892: "These hot currents would almost stop one's breathing. I was caught in the center of one about one hundred feet in width, and it was almost insufferable."[1] The dry heat tends to excessive irritability and nervousness in many cases, insomnia being a frequent result. A correspondent writes from western Kansas during a late June hot wave:

> We have had no rain for several weeks, with daily temperatures in the 90's and a low humidity. For the last several days I have had my first experience of the "hot winds." Today the furniture in my room is cracking in the dry air. I believe, from my own experience, what I formerly doubted, that this dry air inclines to nervousness. Although very tired at night and entirely normal, I often cannot get to sleep for an hour or more. And this, for me, is insomnia.

Weather Map Conditions Favorable for Hot Winds. Most hot winds occur with anticyclonic conditions over the southeast and low pressures over the Dakotas, the pressures decreasing northward and northwestward into Canada, and the depression being nearly stationary or moving slowly along the eastern Rocky Mountain slope and eastward. Under these conditions the general winds over the Plains are southerly and southwesterly, the velocity being greater the steeper the gradient. Occasionally the depression develops over the eastern slope of the Rocky Mountains, and usually there is a trough or V-formation elongated toward the south and southwest from the northern low. Hot winds are also associated with secondary cyclones at the southern extremity of V-shaped depressions that are traveling eastward along the northern boundary of the United States. In view of these relations to low pressure

[1] Quoted by I. M. Cline. See *Amer. Met. Journ.*, Vol. 9 (1892–1893), pp. 437–443.

systems, it is natural that hot wind conditions should gradually move eastward with the eastward progression of the general pressure distribution upon which they depend. In connection with any attempt to study the weather map conditions of hot wind occurrence, it must be remembered that the maps present the facts at one moment only (8 A.M., Eastern standard time) in each twenty-four-hour interval. The wind directions and the temperatures shown on the maps at the various stations are therefore unlikely to be those observed while the hot winds were blowing at those stations.

Cause of the Excessive Heat and Dryness of Hot Winds. There has been a good deal of discussion as to the fundamental cause of the extreme heat and the very low relative humidity characteristic of the true "hot winds" of the Plains. One group of writers (among whom are W. M. Davis[1] and I. M. Cline[2]) has held that these winds have a special and peculiar intensity of heat and dryness which distinguishes them from the general hot wave in which they occur. This characteristic is attributed not simply to the heat imported by the horizontal flow of southerly winds which have blown across hot land surfaces, but also to the presence of descending currents from a considerable height, starting at fairly high temperatures and then warmed adiabatically by compression during their descent. In other words, they are somewhat similar to chinook, or foehn, winds. There are difficulties in accepting this theory, for it is not easy to see how such superheated, and therefore light, local currents of air can be forced down, over extended level plains, into a general body of air which is cooler and therefore heavier than they are. If the initial downward impulse is present, it is conceivable that the momentum of the descending air may be sufficient to carry the "hot wind" currents below the level of their equilibrium. As evidence of such dynamic heating it has been pointed out that there have been numerous cases in which the temperature was lower and the humidity higher over the districts to the south of the hot wind area, and that hot winds have occurred at night and after rain. It would therefore seem

[1] W. M. Davis, "Elementary Meteorology" (1894), p. 233.

[2] I. M. Cline, loc. cit.

as if local surface warming of the air in a hot wind could not fully account for the heat and dryness. Cline believes that the dry air which has been dynamically heated is carried forward aloft faster than below, and descends here and there through moister and less dense air, which rises and forms the scattering clouds often observed.

The second group of writers, including A. J. Henry and the late G. E. Curtis, holds that local excessive heating of the dry earth's surface under clear skies and intense insolation, especially where that surface is barren or sandy, is a sufficient explanation of the heat and dryness of the hot winds. It is pointed out that hot winds do not occur when the soil is moist, that rains quickly bring them to an end, and that they are essentially diurnal phenomena. Favorable local conditions, both of temperature and of moisture, doubtless play a part.

The question which of these two views is the correct one need not be debated here. More complete observations of these interesting phenomena, and especially more data from the free air, will in time lead to a fuller understanding. It is clear that hot winds will always continue to be a serious climatic handicap over the districts in which they occur. Perhaps eventually, with improved methods of conserving soil moisture and with the planting of wind-breaks, some of the blighting effects of these winds upon growing crops will be somewhat mitigated.

Description of a Chinook Wind.[1] Picture to yourself a wild waste of snow, wind-beaten and blizzard-furrowed until the vast expanse resembles a billowy white sea. The frigid air, blowing half a gale, is filled with needle-like snow and ice crystals which sting

[1] For further details see: M. W. Harrington, "The Chinook Winds," *Amer. Met. Journ.*, Vol. 3 (1886–1887), pp. 330–338, 467–475, 516–523; H. A. Hazen, "Chinook Winds," *M. W. R.*, Vol. 16 (1888), pp. 19–20; H. H. Ballou, "The Chinook Wind," *Amer. Met. Journ.*, Vol. 9 (1892–1893), pp. 541–547 (gives short bibliography); A. T. Burrows, "The Chinook Winds," *Yearbook U. S. Dept. of Agriculture, 1901*, reprinted in *Journ. Geogr.*, Vol. 2 (1903), pp. 124–136; A. J. Henry, "Climatology of the United States," *U. S. Weather Bur. Bull. Q* (1906), pp. 72–73; Cleveland Abbe, "The Wet and Dry Chinooks," *M. W. R.*, Vol. 35 (1907), pp. 176–177; L. H. Daingerfield, "Chinook Winds in Eastern Colorado during December, 1907," ibid., Vol. 36 (1908), pp. 87–88; "Weather Forecasting in the United States," *U. S. Weather Bur. No. 583* (1916), pp. 315–316, 323, 332–334 (with weather maps illustrating chinook conditions); F. J. Bavendick, "Blizzards and Chinooks of the North Dakota Plains," *M. W. R.*, Vol. 48 (1920), pp. 82–83.

the flesh like the bites of poisonous insects, and sift through the finest crevices. . . . Great herds of range cattle, which roam at will and thrive on the nutritious grasses indigenous to the northern slope, wander aimlessly here and there, or more frequently drift with the wind in vain attempts to find food and shelter; moaning in distress from cold and hunger, their noses hung with bloody icicles, their legs galled and bleeding from breaking the hard snow crust as they travel. . . . Would the chinook never come? The wind veered and backed, now howling as if in derision, and anon becoming calm, as if in contemplation of the desolation on the face of nature, while the poor dumb animals continued their ceaseless tramp, crying with pain and starvation. At last, on December 1, at about the hour of sunset, there was a change which experienced plainsmen interpreted as favorable to the coming of the warm southwest wind. At sunset the temperature was only −13°, the air scarcely in motion, but occasionally seemed to descend from overhead. Over the mountains in the southwest a great bank of black clouds hung, dark and awesome, whose wide expanse was unbroken by line or break; only at the upper edge, the curled and serrated cloud, blown into tatters by wind, was seen to be the advance courier of the long-prayed-for chinook. How eagerly we watched its approach! How we strained our hearing for the first welcome sigh of the gentle breath! But it was not until 11.35 P.M. that the first influence was felt. First, a puff of heat, summer-like in comparison with what had existed for two weeks, and we run to our instrument shelter to observe the temperature. Up goes the mercury, 34° in seven minutes. Now the wind has come with a 25-mile velocity. Now the cattle stop traveling, and with muzzles turned toward the wind, low with satisfaction. Weary with two weeks standing on their feet they lie down in the snow, for they know that their salvation has come: that now their bodies will not freeze to the ground.

The wind increases in strength and warmth; it blows now in one steady roar; the temperature has risen to 38°; the great expanse of snow 30 inches deep on a level is becoming damp and honeycombed by the hot wind.

Twelve hours afterward there are bare, brown hills everywhere; the plains are covered with floods of water. In a few days the wind will evaporate the moisture, and the roads will be dry and hard. Were it not for the chinook winds the northern slope country would not be habitable, nor could domestic animals survive the winters.[1]

[1] A. B. Coe, "How the Chinook came in 1896," *M. W. R.*, Vol. 24 (1896), p. 413.

There have been many general accounts of chinook winds in the United States, but few, if any, first-hand descriptions have been printed as vivid, as complete, and as accurate as the one just quoted, written by the Voluntary Observer of the Weather Bureau at Kip, Montana, after a well-marked occurrence of this phenomenon in November, 1896.

Another account, by a former student,[1] is as follows:

> One need only stay for a short time in the Missouri valley region of Montana to see the effects of the chinook—popularly called here "the Montana monsoon." At Great Falls the winds were preceded by three or four days of clear, cold weather, with the temperature ranging from zero to −20°. A general rise in temperature began with a slight wind from the southwest. Each day the winds grew stronger and the temperature rose. On the third day after the winds were observed I noted a temperature of about 40° for the whole of one day. I drove twenty-four miles one day across perfectly level bench land, and it was remarkable with what steadiness the wind blew—not a gust or flurry was felt.

Again, from another correspondent in Montana (dated Butte, December 10, 1910):

> Here is something that actually happened one day when I was in Great Falls two years ago. There had been a cold spell for over a week; the temperature had fallen to more than −30°, and averaged −20° for the week. I shall never forget that cold week. We used to sit on the radiator in the office all day to try to keep warm, and when we got away from the radiator we were cold again in a few minutes. This particular day at about a quarter past seven when I went to breakfast it was about −20°, and about 2 P.M. the temperature was well above 32°. The main street in Great Falls was water all over, where previously there had been several inches of snow. This chinook lasted three or four days, and it was nearly like summer while it lasted. A chinook will last from a few hours to a few days. It blows from the southwest, and is not only warm but also very effective in melting the snow.

General Characteristics of Chinook Winds. The chinook wind is a characteristic feature of the eastern slope of the Rocky Mountains in Montana and Wyoming and as far south as

[1] H. S. Thompson. Dated Butte, Montana, December 23, 1905 (unpublished).

Colorado. It is also noted (but has not been so well studied) elsewhere in the northern mountain regions of the West, as in the Black Hills of South Dakota, in eastern Washington and Oregon, in Idaho, Colorado, Montana, western Nevada, and other sections. Occasional rather doubtful occurrences have been reported even farther east, quite well out on the northern Plains. As fuller meteorological observations become available for this area, many occurrences of this wind, not heretofore discussed, will come to light. The late Cleveland Abbe pointed out that a chinook-like wind also appears along the eastern base of the Appalachians.

The chinook is a warm and dry wind, similar in all respects to the Swiss foehn. Its direction along the eastern Rocky Mountain slope is in general southwest (that is, it blows from the mountains out onto the Plains), but its direction is determined by the topography. It begins at any hour, day or night. In velocity it varies from a gentle breeze to a gale. It may blow steadily for many hours, or come in shorter spells interrupted by much colder and calmer intervals. It may last three or four days. It usually begins as a succession of light breezes. Extraordinary stories are told regarding the warmth of the chinook, and this feature is abundantly established by reliable instrumental records. Coming after a spell of intense cold, it is often described as soft and balmy "like a summer zephyr." The preceding temperature may be 20° or 30° below zero, and the rise frequently amounts to 20° to 40° in fifteen minutes. Abbe reported a case at Havre, Montana, March 7–8, 1900, in which the thermometer rose suddenly, shortly after midnight on March 7, from 11° to 42° in three minutes. After remaining nearly stationary for several hours the temperature fell from 44° to 18° in three minutes, and in twenty minutes more it fell to 11°. Between about 5 and 6 A.M. on March 8 it rose from 20° to 40°. After a few hours it began to fall rapidly again, and in an hour and a half it dropped from 43° to 9°.[1] These rapid fluctuations are due to the alternation between the warm

[1] Cleveland Abbe, "Sudden Temperature Changes in Montana," *M. W. R.*, Vol. 28 (1900), pp. 115, 161–162 (with reproductions of two thermograph curves traced during chinook winds).

chinook and the general conditions of cold which assert themselves as soon as the chinook ceases to blow. There is a surging back and forth of the cold air which normally covers the lowlands in winter, and which is temporarily displaced by the warm air of the chinook. Many other instances of remarkable temperature changes might be cited. Occasionally changes of nearly 100° take place within a few days. A rise of as much as 40° in fifteen minutes is, however, rarely attained. The maxima during chinook winds are seldom over 40°, but a rise from below zero to 40° or 45° in a few hours is clearly a very marked phenomenon, and one which inevitably has important economic and physiological effects. Isolated areas of relatively high temperature may thus be produced where chinook winds are blowing along the eastern base of the Rocky Mountains, and these "islands" of warmth occasionally appear on the regular daily weather maps if the warm winds happened to be blowing at the time of the regular 8 A.M. (Eastern standard time) observations on which the weather map is based.

The sky is usually fair or clear over the Plains during a chinook, but over the mountains down from which the wind blows, dark chinook clouds are seen, and at the summits and on the farther slopes rain or snow may be falling. Burrows has pointed out that the chinook does not always follow the mountain slopes closely as it descends, but may be blowing on the upper slopes, passing aloft across a belt at the base, and then appear again at the surface at some distance—one hundred or more miles—from the foot. Under such conditions there is a belt of very low temperatures along the base of the mountains, with moderate temperatures higher up on the slopes and out on the Plains. Travelers crossing the Rocky Mountains in Montana in winter often meet this phenomenon. The case is cited of an eastbound passenger train on the Northern Pacific Railway which left the summit of the pass with mild weather and temperatures above freezing, and in half an hour had descended into a district where the temperature was −13°.

Origin and Use of the Name "Chinook." It appears that the term "chinook" as applied to a wind was first used in western Oregon and Washington, and also in British Columbia, to

designate a warm, moist southwesterly wind coming from the general direction of the district formerly inhabited by the Chinook Indians on the lower Columbia River. It was—perhaps quite independently of this particular use of the term—applied by early settlers along the eastern base of the Rocky Mountains to the warm dry wind descending the eastern slopes of these mountains, which was then, and unfortunately still is, thought by many persons to owe its high temperature to the warm waters of the Pacific Ocean. The name is often applied at the present time to the warm, damp southwesterly winds on the coasts of Washington and Oregon, but its use should be limited to the warm and dry descending winds, of distinct foehn type.

Weather Map Types Favorable for the Occurrence of Chinook Winds. The general pressure distribution favorable for chinook winds along the eastern base of the Rocky Mountains in Montana and adjacent districts is a high over the central Plateau and a low moving eastward from British Columbia to Manitoba and appearing on the United States weather map to the north of the northern Plains. Such a condition results in a general flow of air from the southwest, across the mountains, and then down onto the lowlands to the east, the steepness of the barometric gradient determining the velocity of the wind. Chinook winds may blow at any time of the year, but they are most common in winter because the pressure distribution is then most likely to be favorable and because the temperature changes are then most marked and noticeable. A fairly persistent anticyclone (continental high) is a characteristic of the Great Basin region much of the time during the winter months, with cold weather. When at the same time the pressure is low on the eastern slope, conditions are favorable for the blowing of chinook winds and hence for mild weather in the latter region. Chinooks will occur on the western slopes of the mountains whenever the gradients are such as to cause a flow of air across the ranges to the west, but up to the present time they have received far less attention than has been the case with those on the eastern slopes, where they are more common because most of the cyclonic storms pass eastward along the northern boundary from the Alberta district. The reason that

these winds do not occur farther to the southward is to be found partly in the difference in the cyclonic and anticyclonic controls and partly in the more uniform temperature distribution in lower latitudes. They have been described as far south as southern Colorado, where they occur when a low pressure area or trough extends farther south than usual along the eastern base of the Rocky Mountains.

Origin of the Warmth and Dryness of the Chinook Wind. There is no mystery about the high temperature and the low relative humidity of the chinook. The explanation of the Swiss foehn given fifty years ago by Hann applies equally well to the American chinook. Under the prevailing pressure distribution the air of the chinook is forced to descend rapidly from the mountain tops to the lowlands. In doing so it is warmed dynamically and its capacity for water vapor increases, so that it becomes relatively drier. Free air observations have shown that the temperature aloft is even higher than that at the surface. When the air of the chinook has first ascended the western slopes of the mountains before descending on the leeward side, an additional source of warming is available through the liberation of latent heat in the process of the condensation of water vapor into rain or snow on the windward slopes.

Economic Aspects of Chinook Winds. During the colder months chinook winds are important factors in the local climates of the northwestern mountain states. They temper the severity of the winters, bringing welcome relief from the extreme cold and, when they occur often, distinctly raising the mean monthly and annual temperatures. The most marked temperature changes which take place during the winters of western Montana are due to chinook winds following severe cold. But it is their extraordinary effect in melting and evaporating the snow that has attracted the most attention. It is impossible to overestimate their economic importance to the cattle interests, as is pointed out in the graphic description of a chinook quoted at the beginning of this section. The coming of a chinook at a critical period saves thousands of cattle from starvation and freezing. The warmth melts the snow, as one correspondent expresses it, "just as though hot water or steam

were directed against it." Because of this wind, stockmen can get through the winter with much less stacked hay than would otherwise be required. Domestic and other animals exposed to the severe winter weather outdoors without shelter are not only able to secure food because of the chinook, but find in its warmth a welcome relief in their hard fight against the cold.

Evaporation and melting are so rapid that a foot of snow may disappear within a few hours, being "sucked up from the ground" without even a trickle of water, as one description has it.[1] At Helena, Montana, a snow cover ten inches in depth has disappeared over night, leaving a dry surface the next morning. In midwinter as much snow will disappear during a few hours of mild and balmy chinook weather as would melt in the same number of days of the usual spring thaw. Chinooks aid greatly in keeping the railroads free from snow blockades, and by favoring a melting and then a freezing of the snow in the mountains they may store up water in the form of ice for summer irrigation. The chinook, to quote Burrows, "is an ever-welcome guest whose coming is indicative of good, and whose absence would be a momentous evil."[2] There are, on the other hand, a few drawbacks. In the case of many persons the warm dry wind has unpleasantly stimulating effects on the nerves, and because of the dryness, chinook weather is considered especially dangerous by the fire patrols in the national forests.

Winds of Chinook Character in California: Norther and Santa Ana.[3] A marked climatic characteristic of the climate of Cali-

[1] *M. W. R.*, Vol. 35 (1907), p. 176.

[2] A. T. Burrows, "The Chinook Winds," *Journ. Geogr.*, Vol. 2 (1903), p. 136.

[3] See "Meteorology in California," *Amer. Met. Journ.*, Vol. 3 (1886–1887), pp. 206–209; W. A. Glassford, "Weather Types on the Pacific Coast," *Bull. Cal. Acad. Sci.*, No. 5 (August 31, 1886), pp. 77–88; B. S. Pague and S. M. Blandford, "Weather Forecasting and Weather Types on the North Pacific Coast," *U. S. Weather Bur.* (Portland, Oregon, 1897), pp. 10–13, 22–24; A. G. McAdie, "Climatology of California," *U. S. Weather Bur. Bull. L* (1903), p. 17; idem, "Fog and Frost in the San Gabriel Valley," *M. W. R.*, Vol. 38 (1910), p. 1895; Archibald Campbell, "Sonora Storms and Sonora Clouds of California," *M. W. R.*, Vol. 34 (1906), pp. 464–465; T. A. Blair, "Northers of the Sacramento Valley," ibid., Vol. 37 (1909), pp. 132–133; F. A. Carpenter and J. W. Garthwaite, "Memorandum on Air Drainage in the Vicinity of the Corona District, California," ibid., Vol. 42 (1914), pp. 572–573 (gives photographs of a norther dust cloud and of a hygrograph record during a norther; also weather map showing pressure distribution favorable for northers in southern California).

fornia, both in the great valleys of the north and also in the smaller valleys south of the Sierra Madre, is an occasional strong northerly wind which, during the warmer months, especially in late spring and early summer, has desiccating qualities causing it to be much dreaded by farmers and fruit-growers. This norther derives its drying power from the fact that it has been dynamically warmed by compression during its descent from the mountains and plateaus. In other words, it is of chinook nature. It blows when the pressure is highest to the north and when there is a deepening of the usual summer low over southeastern California and the Colorado valley, and usually lasts from one to three or four days. During the summer months this wind is very hot as well as dry. A fire that caused considerable loss at Berkeley, California, in September, 1923, and might have wiped out the University of California, occurred during a norther. The humidity is so low during the prevalence of these winds that grass, brush, timber, etc., are thoroughly dried out and supply quick-burning fuel. Hence it is wise at such times to take special precautions against fires.[1] The norther often seriously injures vegetation, drying fruit and scorching and killing young leaves. The soil dries up and cracks. Human beings suffer from nervousness and headaches and become irritable and impatient. It is said that in the early days in California if a murder or any personal violence resulted from a quarrel which occurred during a norther that fact was taken into account as an extenuating circumstance. During a norther cattle are restless and cows are reported to give less milk than usual.

In southern California, in the vicinity of Los Angeles, the norther, under topographical control, may blow from northeast or from other directions. It is locally known as the Santa Ana because of its association with the pass and river valley of that name. In San Diego County the hot dry wind comes from the east. If such a wind blows at a critical time in the life of the fruit trees, in spring, it may do considerable damage.[2]

[1] See also G. W. Alexander, "Weather and the Berkeley Fire," *M. W. R.*, Vol. 51 (1923), pp. 464–465.

[2] Archibald Campbell, "The Santa Anna or Desert Winds," *M. W. R.*, Vol. 34 (1906), p. 465.

Carpenter and Garthwaite have published an excellent photograph of the dust cloud preceding a norther in the Los Angeles district.[1] With increasing velocity of the wind this cloud becomes thicker and more extended and finally obscures everything. At Claremont, Pomona County, California, at 4 P.M., March 18, 1914, the relative humidity during a norther was recorded on the hygrograph as 5 per cent, with a possible error of from 4 to 6 per cent. In four hours it rose to 97 per cent, with the cessation of norther conditions. McAdie reports that he has himself seen three overland trains practically brought to a stop in the face of a sand-laden norther blowing through El Cajón Pass in southern California, and automobiles had to be abandoned twenty miles west of Riverside.[2]

[1] F. A. Carpenter and J. W. Garthwaite, loc. cit., Fig. 3.
[2] Alexander McAdie (in manuscript).

CHAPTER XIX

LAND AND SEA BREEZES AND MOUNTAIN AND VALLEY WINDS

LAND AND SEA BREEZES · MOUNTAIN AND VALLEY WINDS

Land and Sea Breezes. Along the Atlantic, Pacific, and Gulf coasts, and also on the shores of the Great Lakes, the diurnal onshore and offshore winds known as land and sea breezes, or as lake breezes, often have considerable local climatic importance. In fine, quiet, anticyclonic weather during the warmer months, when the days are hot, the cool breeze from the water has a decided effect in lowering the diurnal temperature maximum and is thus a welcome visitor. General cloudiness, rain, and strong storm winds prevent its development. It lasts at best only a few hours. It penetrates only a few miles inland. Yet it tempers what without it would often be uncomfortably hot and disagreeable days. Where local conditions are favorable the sea breeze may be a fairly regular occurrence. Therefore it is in many places a factor of real economic value in adding to the attractions of seashore resorts. The offshore land breeze, blowing at night, attracts much less attention and is also of less importance.

These breezes are greatly influenced in direction, velocity, and duration by local topography. They are also often combined with the prevailing winds, modifying the latter as to velocity or direction, or both. Thus, if the prevailing wind happens to be onshore, the sea breeze usually increases this wind during the warmer hours of the day. If it is strong enough the nocturnal land breeze may overcome the onshore current entirely and result in an offshore movement during the night. These various combinations are significant in the study of local littoral climates and deserve more attention than they have hitherto received.

The most complete study of the sea breeze for any part of the United States is that by Davis, Schultz, and Ward for New England.[1] Under favorable conditions of quiet, warm, late spring and summer anticyclonic days, the fresh cool breeze from the Atlantic usually reaches the coast between 9 and 10 in the morning, although it may appear as early as 8 A.M. or as late as noon. Its duration is until 3 or 4 P.M., or perhaps later. The rate of advance inland is from three to eight miles an hour at the start, and then slower. As its hourly velocity (from ten to fifteen miles) is somewhat greater than its rate of advance, an ascent of the breeze at its inland margin is inferred. The frequent development of afternoon thunderstorms near the coast on sea-breeze days is probably connected with this fact. The cooling effect of the sea breeze is distinctly marked on the coast, but soon weakens with increasing distance inland.

Smock has called attention to the striking development of the sea breeze on the low sandy shores of New Jersey, where it adds greatly to the popularity of the many summer resorts.[2] On Long Island, New York, the sea breeze in general penetrates inland about ten miles, but on the southern shore, where it is combined with the prevailing southerly wind, both its velocity and its penetration are considerably increased.[3] On the northern coast of Long Island Sound the prevailing westerly wind shifts from northerly at sunrise to southerly at noon in fine summer weather under the control of the sea-breeze influence.[4] Incidental mention of the sea breeze at other points along the Atlantic and Gulf coasts occurs in the regular reports

[1] W. M. Davis, L. G. Schultz, and R. DeC. Ward, "An Investigation of the Sea Breeze," *Annals Astron. Obs. Harv. Coll.*, Vol. 21, Part II (Cambridge, Massachusetts, 1890), pp. 215–263 (contains references to early writings on the sea breeze in the United States). For other local studies of the sea breeze in New England see W. C. Appleton, "The Sea Breeze at Cohasset, Massachusetts," *Amer. Met. Journ.*, Vol. 9 (1892–1893), pp. 134–138; G. B. Magrath, "The Sea Breeze at Boothbay Harbor, Maine," ibid., Vol. 11 (1894–1895), pp. 10–14.

[2] John C. Smock, "Final Report of the State Geologist," *Geol. Survey of N. J.*, Vol. 1 (Trenton, New Jersey, 1888), pp. 348, 356–357.

[3] E. T. Turner, *Fifth Ann. Rept. Met. Bureau and Weather Service of the State of N. Y., 1893*, State of New York, Dept. of Agric. (Albany, New York, 1894), pp. 365–366; idem, "The Physical Geography of New York State," *Bull. Amer. Geogr. Soc.*, Vol. 32 (1900), pp. 101–132, especially p. 115. See also Ernest S. Clowes, "Sea Breeze on Eastern Long Island," *M. W. R.*, Vol. 45 (1917), pp. 345–346.

[4] W. M. Davis, "Elementary Meteorology" (1894), p. 137.

of the various states bordering on these bodies of water,[1] but local studies of the phenomenon are singularly few in number.[2]

Around the Great Lakes the onshore lake breezes of hot summer days have cooling effects similar to those of the sea breeze. Cox and Armington have described the lake wind at Chicago. When conditions are favorable this wind is felt over the entire city, but it may be so light as not to be noticeable over the western and southwestern sections.[3] On July 21, 1901, during a severe hot wave, a shift of wind to the lake lowered the temperature from 102° to 84° in one hour. While this is a remarkable case, Chicago's summer heat is often considerably tempered by its pleasantly refreshing breeze from Lake Michigan. Other studies of lake breezes have been made by Miller for the peninsula of upper Michigan and of northern Wisconsin[4] and by Eshleman for Grand Haven, Michigan.[5] In most cases the lake breeze merely serves to modify somewhat the direction of the prevailing wind. Thus, along the shores of Lake Erie, in Ohio, the westerly wind of summer is, under favorable conditions, deflected into a northwesterly wind by day and into a southwesterly wind by night, the shore line being about parallel to the course of the general wind.[6]

On the Pacific coast, especially in California, the conditions are different. There the prevailing onshore westerly winds are intensified by the sea-breeze effect during the day, so that considerable velocities may be developed. The offshore nocturnal

[1] See, for example, the Summaries of Climatological Data by Sections, *U. S. Weather Bur. Bull. W.*

[2] Note, however, a recent paper by C. E. Heckathorn, "Land and Sea Breezes in the Vicinity of Corpus Christi Bay, Texas," *M. W. R.*, Vol. 47 (1919), pp. 413–415.

[3] H. J. Cox and J. H. Armington, "The Weather and Climate of Chicago," *Geogr. Soc. of Chicago Bull. No. 4* (1914), pp. 44, 142–145. See also H. A. Hazen, "Report on Wind Velocities at the Lake Crib and at Chicago," *U.S. Signal Service Notes*, No. VI, 1883 (gives a striking illustration of the regular veering of the afternoon lake breeze into the land breeze at night, with a sudden reversal into the former at noon).

[4] E. R. Miller, "The Meteorological Influences of Lakes," *Proc. 2d Pan-Amer. Sci. Congr., December 27, 1915, to January 8, 1916.* Sect. II: Astronomy, Meteorology, and Seismology (Washington, D.C., 1917), Vol. II, pp. 189–198.

[5] C. H. Eshleman, "Climatic Effect of the Great Lakes as Typified at Grand Haven, Mich.," *Met. Chart of the Great Lakes*, September, 1913, United States Weather Bureau.

[6] W. M. Davis, loc. cit.

land breeze, on the other hand, may completely overcome the prevailing wind, reversing it to a light breeze from land to sea at night, or there may be a calm instead of the offshore wind. At San Francisco, for example, because of the local topography, the onshore wind becomes exceptionally strong during the daytime in the warmer months. Such winds are hardly to be called sea breezes in the ordinary meaning of that term, although they are commonly so designated. In southern California, for example, they prevail throughout most of the year, attain considerable vertical extent, and extend well inland where the topography favors them. As Hann pointed out many years ago, this wind "partakes rather of the character of a monsoon, because it is an effect of the prevailingly higher temperature in the interior of California as compared with the ocean."[1] The cool summers of the coast are to a large extent due to these strong onshore diurnal winds. Wright has discussed the sea breeze at San Francisco,[2] and Carpenter has emphasized the development and local importance of the land and sea breezes at San Diego.[3]

Mountain and Valley Winds. In hilly and mountainous districts, under favorable conditions of clear weather and an absence of strong surface winds, mountain and valley winds are often of considerable local interest and even of economic and physiological importance. When the cool downstream air currents from the smaller side valleys are concentrated in some one larger valley, emerging on an open plain, the nocturnal mountain wind may attain a considerable velocity at the mouth of the main valley. Because of its effect in lowering the temperature, and also because its velocity is apt to attract attention, the cool mountain wind of the evening and night is much more generally observed and described than the warm up-slope valley wind of the day.

[1] J. Hann, "Handbook of Climatology," Vol. 1 (2d ed.), p. 157. Translated by R. DeC. Ward, 1903.

[2] H. H. Wright, "Fog in Relation to Wind Direction on Mount Tamalpais, California," *M. W. R.*, Vol. 44 (1916), pp. 342–344; idem, "Certain Characteristics of the Winds at Mount Tamalpais, California," ibid., pp. 512–514 (the estimated height of the sea breeze is from 800 to 1000 feet).

[3] F. A. Carpenter, "The Climate and Weather of San Diego, California" (San Diego, 1913), pp. 54–56.

In spite of their widespread occurrence in many parts of the United States, these members of the wind system have thus far received comparatively little attention. Scattered accounts of them have appeared here and there in the literature of the West, in which region both topography and weather types are especially favorable to their development. In many places they attain very considerable velocity, occur with much regularity, and are important local climatic controls. There, also, the up-slope valley wind of daytime is an effective agent in the development of afternoon mountain thunderstorms. In the warmer months such thunderstorm rains often occur with great regularity, day after day.[1] Matthes has given an unusually full description of the very pronounced mountain and valley winds of the Yosemite.[2] Ascending winds occur on the warm, sunny slopes, and descending winds are noted on the shady slopes. In order to avoid the dust caused by these strong winds the writer several times planned his trips with reference to the conditions as he had observed them during his geological field work in that area. "With nightfall there is organized a great system of confluent air streams corresponding closely to the valley system of the land"; there are downstream breezes from "every side valley or canyon." In order to see at their best the conditions which gave Mirror Lake its name, that body of water should be visited at an early hour in the morning, during the period of calm between the nocturnal and diurnal winds. In the afternoon the reversal from one wind to the other is much less likely to be associated with a calm interval.

[1] See, for example, W. M. Davis, "Mountain Meteorology," *Appalachia*, Vol. 4, No. 4 (1886), p. 334 (reference to mountain winds "blowing with very unpleasant strength out of the lower cañon of the Yellowstone—and again at the narrow mouth of Boulder Creek, whose branches flow from a large area within the Big Belt Mountains"); W. S. Tower, "Mountain and Valley Breezes," *M. W. R.*, Vol. 31 (1903), pp. 528–529 (description of the winds observed in southwestern Colorado); B. M. Varney, "Daytime Wind Turbulence in a Mountain Valley," ibid., Vol. 48 (1920), pp. 336–337 (an example of wind turbulence in the daytime wind near Yosemite valley); Summary of the Climatological Data of the United States by Sections, *U. S. Weather Bur. Bull. W*, sect. 7 (note on the mountain and valley winds below the Royal Gorge, Colorado). Many other scattered references might be added.

[2] F. E. Matthes, "The Winds of the Yosemite Valley," *Sierra Club Bulletin*, Vol. 8, No. 2 (June, 1911). Reprinted in *M. W. R.*, Vol. 39 (1911), pp. 1257–1259.

In the East, where the topography is less marked, these winds are less noticeable. Turner has called attention to the mountain and valley winds at Ithaca, New York, and to their combination with the prevailing winds at Utica, New York.[1] Clowes has shown the influence of mountain and valley winds on the prevailing wind direction at Syracuse, New York,[2] and Cox has more recently called attention to the local importance of mountain breezes in the Appalachian Mountains of North Carolina.[3] Exposure to nocturnal mountain breezes may be a factor well worth taking into account in the selection of house sites and in the location of sleeping-porches and windows in planning summer dwellings. Some years ago the author had a personal experience in New Hampshire with the cool down-slope breezes on hot summer nights. The location of his house was on a gentle slope at the mouth of a small valley. A neighbor had built a house on a near-by hilltop, thinking that that site would give a free exposure to cooling winds. In the former case, although the elevation was two or three hundred feet lower, a refreshing cool breeze blew down the valley and through the open windows every clear, quiet night following a hot day, whereas the neighboring house on the hilltop had no such breeze.[4] In the case of another neighbor, whose house was located on a hill slope, and who asked for advice as to the best side on which to build a sleeping-porch, the reply was to put it on the up-slope side, although the down-slope side was exposed to the prevailing daytime wind. Campers in mountain regions have frequent experience with the descending air currents of night-time. The fire should be made below a camp situated on a slope, in order that the smoke may move downhill, away from the camp. When the descent of the air down

[1] E. T. Turner, "The Climate of the State of New York," *Fifth Ann. Rept. Met. Bureau and Weather Service of the State of N. Y.* (Albany, New York, 1894), pp. 388–390. See also F. B. White, "Topographic Influence on the Winds of the Weather Maps," *Amer. Met. Journ.*, Vol. 12 (1895–1896), pp. 15–19.

[2] E. S. Clowes, "Mountain and Valley Winds at Syracuse, New York," *M. W. R.*, Vol. 47 (1919), p. 464.

[3] H. J. Cox, "Thermal Belts and Fruit Growing in North Carolina," *M. W. R. Supplement No. 19* (1923), p. 34.

[4] See also C. F. Brooks, "Local Climates of Worcester, Massachusetts, as a Factor in City Zoning," *Bull. Amer. Met. Soc.*, Vol. 4 (1923), pp. 83–85.

the slopes is slow, the cooling by radiation and conduction to the cold ground results in a lowering of the temperature, and the mountain wind is cool. In a region of marked topography, however, and under favorable conditions of a concentration of air currents and a resulting strong wind, the warming by compression may overbalance the cooling. Hence the mountain breeze may become warmer than the surrounding air, and may produce a frostless area at the mouth of a valley opening out on a plain.[1]

Special cases of descending winds during the daytime have been observed in many countries where the air in a valley is chilled by a local glacier, and therefore blows down-slope. Reid has described the occurrence of such glacial breezes at the foot of the Muir Glacier, on the coast of Alaska.[2]

[1] W. M. Davis, "Elementary Meteorology" (1894), p. 139; H. J. Cox, loc. cit.

[2] H. F. Reid, "Studies of Muir Glacier, Alaska," *Nat. Geogr. Mag.*, Vol. 4 (1892), pp. 19–84.

CHAPTER XX

THE ESSENTIAL CHARACTERISTICS OF UNITED STATES CLIMATES[1]

THE EASTERN PROVINCE · THE GULF PROVINCE · THE PLAINS PROVINCE · THE PLATEAU PROVINCE · THE PACIFIC PROVINCE

The Eastern Province. The essential characteristics of the climates of the United States, details of which have been considered in the foregoing chapters, may now be briefly summarized and reviewed. The Eastern Province, enormous as is its extent, is nevertheless characterized by great uniformity in its climatic conditions and in its weather types. It has a continental climate, but with abundant or at any rate sufficient rainfall. Over most of it the seasons are strongly contrasted. The summers are very warm and the winters cold. But the hot summers, with sufficient rainfall, usually insure abundant harvests; and the cold winters, while severe in northern sections, are on the whole stimulating and tonic. The influence of the Atlantic Ocean is minimized by the fact that the prevailing winds are offshore throughout the year, being northwest in winter over much of the coast and southwest in summer. Thus it follows that there can be but little of the tempering effect usually associated with conservative ocean waters; and the coastal belt, except when the wind blows onshore under general cyclonic or anticyclonic controls, or when in summer local sea breezes occur, does not differ very much from the interior. One aspect of this situation is clearly illustrated on the chart of equal annual ranges of temperature. The large ranges of the interior are carried eastward to the coast, and

[1] Reference may be made to the following papers: R. DeC. Ward, "Two Climatic Cross-Sections of the United States," *M. W. R.*, Vol. 40 (1912), pp. 1909–1917; idem, "Lorin Blodget's 'Climatology of the United States.' An Appreciation," ibid., Vol. 42 (1914), pp. 23–27.

even onto the ocean for some distance offshore. The continentality of the Atlantic coast climate, with its slight marine modifications, was well described by Blodget when he wrote that on the immediate coast "a local oceanic climate exists, but it is always blended with the continental features which belong to this part of the continent generally."[1]

There are only relatively slight and unimportant differences of topography. The whole area is freely open to Canada on the north, to the Atlantic Ocean on the east, and to the Gulf of Mexico on the south. With the warm Gulf on the south and the cold Canadian plains on the north, the winter temperature gradients between north and south are unusually steep. In January the isotherms over the eastern United States are very closely crowded together. The temperature then decreases northward at the rate of 2.7° F. in each degree of latitude, both on the Atlantic coast and in the Mississippi Valley. This is an extraordinarily rapid temperature gradient, and may be contrasted with the very much weaker gradient along the western coast of Europe in winter. As seen on the chart of mean annual temperatures, one may go north in western Europe a distance of a thousand miles without finding a change of temperature as great as that met with in half as long a journey along the eastern coast of the United States. In summer North America is well and relatively very uniformly warmed. There is then much less difference of temperature between south and north. The temperature gradient is greatly weakened. It becomes 1.1° along the eastern coast and 0.7° in the Mississippi Valley. The temperature conditions are very broadly generalized in the following table. It should be understood that the data here given are for convenience of ready reference only, and are not to be taken too literally. The maps and diagrams in Chapter V give more detailed information.

District	Mean Annual	January	July	Absolute Maximum	Absolute Minimum
North	40°	5°–10°	65°–70°	100°–105°	–40° to –50°
South	65°–70°	50°–55°+	80°+	100°–105°+	0°–10°+

[1] Lorin Blodget, "Climatology of the United States," 1857.

The average dates of first and last frost may be summarized as follows:

District	Last Spring	First Autumn	Average Length of Growing Season
North	After June 1 (extreme north)	September (extreme north)	3–4 months
South	March	November–December	7 months and over

Besides having a great uniformity of temperature conditions considering its extent, the eastern climatic district of the United States also has a plentiful rainfall, well distributed throughout the year. Disregarding local areas on the mountains, the annual rainfall is greatest (50 + inches) toward the Gulf and on the south Atlantic coast (most of the supply of water vapor for this precipitation coming from the Gulf and the Atlantic Ocean) and decreases from about 40–45 in. over much of the north and central Atlantic coast and Ohio valley to 30–40 in. over the prairies, and 20 in. at the 100th meridian. Although the rainfall is comparatively small at the western margin of the district, it is very well apportioned through the year. The maximum over the great farming states of the Mississippi Valley region comes when it is most needed, in the growing season of late spring and early summer. Of this region it has been well said: "Although droughts sometimes affect considerable districts, and floods occasionally devastate the larger valleys, yet the world hardly contains so large an area as this so well adapted to civilized occupation."[1]

Nowhere in this district is there permanent necessity of irrigation, as there is in many places farther west. The rainfall comes chiefly from the ordinary cyclonic storms of the prevailing westerly winds. The spring and early summer rainfall of the Mississippi Valley and adjacent regions is largely a local thundershower rain, and naturally occurs with the greatest frequency during the warmer months. In the colder season, with high pressures and with winds prevailingly blowing out from the continent, there is less opportunity for precipitation. In

[1] W. M. Davis, "Elementary Meteorology," p. 301.

late summer the rainfall along the Gulf and Atlantic coasts is generally at a maximum, for the inflowing winds are then very warm and moist, and there are many thunderstorms. Along these coasts occasional West Indian hurricanes, in August, September, or October, give heavy rains and not infrequently damage buildings and crops. In Florida the heavy August and September rains are almost tropical in character. In Tennessee and adjacent parts of Mississippi, North Carolina, Georgia, and Alabama there is a late winter or early spring maximum of precipitation.

Rain falls most often, and hence the number of rainy days and the rain probability are greatest, in the Great Lakes region. This same district is also more cloudy than any other portion of the country except the northwest coast. The explanation of these conditions is found in the frequency of cyclonic storms, accompanied by general rains and by extended cloud sheets, over the Great Lakes and along the St. Lawrence valley. Snow falls throughout a long season and in considerable amounts over these same northern and northeastern sections. Toward the south the snow season becomes shorter and shorter; the snow lies on the ground less and less time. It finally becomes an almost, and then an entirely, negligible factor. In the Ohio and lower Mississippi drainage areas floods of greater or less severity are normal. On the Mississippi above Cairo, Illinois, such occurrences are less frequent. Conditions over the Missouri and upper Mississippi drainage basins are not as a rule favorable for producing bad floods. Heavy and prolonged rains, fairly common in certain parts of the country, are not characteristic of these areas. The region is mountainous only in certain sections. The soil is generally porous. There is considerable evaporation. Hence much of the precipitation does not find its way directly into the streams. Further, the Missouri type of rainfall, which is dominant over most of this area, brings the maximum precipitation in early summer, after the winter snows have gone and when the ground is able to absorb the moisture. In the case of the Ohio, which is the chief factor in causing the floods of the lower Mississippi, the situation is different. The Appalachian topography is steep

and rugged. Heavy and prolonged rainfalls are characteristic. Deep snows lie on the mountains well through the winter. The late winter and early spring rains, which are normal over the lower Mississippi Valley and thence eastward, usually bring the Mississippi nearly to the flood stage between Cairo and the Gulf. It is fortunate that disastrous floods result only when these rains are especially heavy over the Ohio drainage area, when the soil is frozen, and when there is much snow on the ground. The breaking up of the ice in the main rivers is an added factor in the situation. The rains most concerned come with storms of the Southwestern, or Texas, type, two or more of which not infrequently follow in quick succession, giving heavy warm rains with high temperatures, under which the snow melts rapidly.[1]

Rapid and marked weather changes are characteristic of the eastern United States. These "paroxysms of change" (Blodget), which occur during the passage of numerous well-developed cyclonic storms, are unique for their suddenness, frequency, and amount, especially in winter. They result from the bringing together, around the passing low pressure centers, of winds of different directions and of very different temperature and moisture conditions, depending upon the characteristics of the regions from which these winds come. The winter dry northwest winds are often piercingly cold, coming as they do directly from the cold continental interior, and may cause a fall of temperature of 30° to 50° F. in twenty-four hours, reducing the temperature to zero or lower (cold waves). They blow on the rear of cyclonic storms and follow warmer and damper southerly or easterly winds which bring rain or snow. Several short periods of extreme cold are to be looked for every winter. During the warmer months similar northwest winds

[1] Reference may be made to the following: Park Morrill, "Floods of the Mississippi River," *U. S. Weather Bur. Bull. E*, 1897; H. C. Frankenfield, "The Ohio and Mississippi Floods of 1912," *U. S. Weather Bur. Bull. Y*, 1913; A. J. Henry, "Floods in New England Rivers," *M. W. R.*, Vol. 42 (1914), pp. 682–686; idem, "The Floods of 1913 in the Rivers of the Ohio and Lower Mississippi Valleys," *U. S. Weather Bur. Bull. Z*, 1913; idem, "The Flood Months in the United States," *M. W. R.*, Vol. 47 (1919), p. 741 (with references); idem, "The Distribution of Maximum Floods," ibid., pp. 861–864. The files of the *Monthly Weather Review* give information regarding all important floods.

bring the summer cool spells. The warmest weather, in winter as in summer, is brought by southerly and southwesterly winds which, coming from lower and warmer latitudes, blow north into a passing storm center. In winter these southerly spells, while unseasonably warm, serve to break the monotony of the cold. In summer, with its high temperatures and high relative humidity, this same sirocco weather type is uncomfortably muggy and depressing and often brings sunstrokes. The summers always bring spells of extreme heat of this type. In winter and spring the northeast cyclonic winds on the northern Atlantic coast are damp and unpleasantly chilly, blowing onshore from the cold ocean waters. In summer their low temperatures bring welcome relief from the heat. In such a region, where sudden and irregular weather changes are so characteristic, climatic averages can give little idea of the actual conditions which are experienced from day to day. Seasons often differ markedly in character from year to year. Weather changes are erratic and unexpected. It has become a popular saying that almost any kind of weather may be expected at any time of the year.

Thunderstorms, many of them of wide extent and of great violence, are characteristic summer phenomena over the eastern and southern United States. The far more severe tornadoes, fortunately of much less frequent occurrence, develop most often over the great lowlands of the central and upper Mississippi and lower Missouri valleys. Tornadoes, as well as the more violent thunderstorms, have a habit of springing up along the dividing (wind-shift) line between the warm southerly (sirocco) type of weather in front of a passing summer cyclonic storm and the cool northwesterly (summer cool wave) type on its rear.

The Gulf Province. Over the southern tier of states bordering on the Gulf of Mexico the temperatures are higher, the winters are much milder, the summers are longer and hotter, and the rainfall is heavier and has a late summer or early autumn maximum. With increasing distance from the most frequented cyclonic paths, which follow along the northern border of the United States, the cyclonic control is weaker; the irregular

wind, temperature, and weather changes are fewer, less sudden, and less emphatic; the diurnal phenomena are more marked, even in winter; the weather is more stable; conditions are more settled. In winter, cyclones which give heavy snows and marked wind changes, followed by cold waves over northern sections, often bring but little cloud and rain, without marked temperature variations, over the Gulf states. The Southern states are, nevertheless, subject to occasional invasions of considerable cold in winter during the prevalence of north and northwest winds on the rear of well-developed cyclonic storms. These winter cold waves sweep east and southeast as far as the southern Atlantic and Gulf coasts, but their intensity diminishes rapidly as they advance into more southern latitudes. The occurrence in districts of high mean annual temperature of frosts of sufficient severity to injure the more sensitive crops is a characteristic of southeastern North America and is one of the marked and, economically, one of the most unfortunate features of the climate of the Gulf Province, which is otherwise in many ways singularly favored. Snow becomes a rarity. Over the sections immediately adjacent to the Gulf it is practically negligible. On the warm, damp lowlands there is the wealth of southern cotton and sugar cane and semi-tropical fruits, and from the truck gardens of the southern Atlantic coast immense quantities of early vegetables are shipped north, by rail and by water, to the markets of the great northern cities. The severe winters in the North put a stop to many outdoor occupations during the colder months, although they give rise to others, such as ice-cutting and lumbering. In the Gulf Province, on the other hand, and over the closely adjoining sections of the Eastern Province, most agricultural and other outdoor work can be continued throughout the year.

The Plains Province.[1] The essential difference between the climate of the Great Plains and that of the Eastern Province is

[1] See a recent discussion by J. B. Kincer, "The Climate of the Great Plains," *Annals Assoc. Amer. Geogr.*, Vol. 13, No. 2 (1923), pp. 67–80. "At present only about 1 per cent of the Plains is under irrigation, but this can be materially increased and, at some future time, irrigation will doubtless be practiced extensively, where climatic conditions other than rainfall are favorable for intensive crop cultivation" (p. 80).

not so much one of general temperature conditions as of rainfall. The Plains, like the rest of the great region lying to the eastward, have a continental climate. They lie at a distance from large bodies of water, and have massive mountain barriers on the west, between them and the Pacific Ocean.

The following table summarizes the temperatures:

District	Mean Annual	January	July	Absolute Maximum	Absolute Minimum
North	40°	0°–10°	65°–70°	105°–110°	−50° to −60°
South	65°	40°–50°	80°–85°	105°–110°	about zero

The average date of the first killing frost in autumn is about September 10 in the extreme northwestern portion, and approximately three months later in the south. The average length of the growing season is from three to four months in the north and over eight months in southern Texas. As compared with the eastern states, the Plains have larger diurnal ranges of temperature, more abundant sunshine, drier air, greater evaporation, smaller rain probability, less rain, and more wind. The prevailing winds have a monsoonal character: they are northerly and northwesterly in winter and southerly and southeasterly in summer. There is a well-marked diurnal variation in velocity on days whose weather is not under strong cyclonic control.

Rainfall is the fundamental climatic factor. From the more abundant precipitation toward the Atlantic and the Gulf, the mean annual rainfall decreases westward until, at the eastern margin of the Plains, it averages about 20 to 25 in., and toward the western margin decreases still further to below 15 in., except where, as in portions of Montana, the diversified topography results in somewhat larger amounts. No sudden change, either in topography or in climate, takes place along the 100th meridian; but where the mean annual rainfall averages less than 15 to 20 in., the amount is too small, under ordinary circumstances, for permanently successful agriculture unless irrigation or special methods are resorted to. Another disadvantage of a small rainfall is its variability from year to year. Remarkable results have been attained by dry-farming methods

over parts of the Plains, in the case of certain crops which require little water, and in seasons with favorable rainfall. Dry farming is, however, a precarious venture and cannot be counted on to give results comparable with those obtained in a well-watered or well-irrigated country. The natural limitations of the Plains are now clearly recognized. Their use in the drier sections is not to be found in the old-time boundless cattle ranges, or in vast farms which depend solely upon the natural rainfall, but rather in smaller individual farms and cattle ranches where irrigation from streams or from ground-water is possible. The relatively high and steady velocities of the winds over the Plains have proved a reliable source of power in driving windmills for pumping water for irrigation. The relation of the 20-inch rainfall line to agriculture was locally recognized a good many years ago. "East of it lies success; west of it, failure. Look out for the 'dead-line.'" Thus an old proverb in that region expressed it. The critical boundary thus termed the "dead-line" played an important part in the settlement and development of the Great Plains.

The distribution of the rainfall in normal years is singularly favorable over most of the Plains Province, especially in the north. The maximum usually comes in late spring or in early summer, when moisture is most needed by the growing crops. To the southward (New Mexico), the maximum is retarded until midsummer or late summer. These warm-season rains are spasmodic and fall chiefly in the form of brief and local thunder-showers. Winter is the dry season. In the north the winter precipitation is mostly in the form of snow, but the amounts are considerably less than those of the same latitudes farther east. Over the southern Plains, where the winters are warmer, the winter snows average under 10 in. in depth, and are even under 5 in. in western Texas and southernmost New Mexico.

Cyclonic control is less marked than in the East, partly because fewer cyclonic storms pass over or near the Plains, and partly because the storms are generally of a milder type. Irregular weather changes are most frequent over the northern Plains states, which are nearer the main storm track. In the south the sequence of weather changes is much more uniform.

Diurnal rather than cyclonic controls are dominant most of the year. The more severe winter cyclones bring sudden temperature changes, severe gales, driving snow, and extreme cold (blizzards). Cold waves, sweeping southward and eastward from western Canada, occasionally reach as far south as Texas, where they cause sudden and marked falls in temperature, with chilling northerly winds (northers). Much of the winter weather, however, is dry, clear, settled, and bracing. Locally, along the eastern base of the Rocky Mountains, the winter cold is often tempered by warm chinook winds. Long spells of hot, dry, typical diurnal weather, with southerly winds, are characteristic of much of the summer. When continued for many days, or sometimes even for weeks, unbroken by general rains or by widespread thundershowers, such spells are associated with extended droughts and result in injury to crops, especially when they are accompanied by certain hot and dry winds which are characteristic of the Great Plains (hot winds). While thunderstorms are of frequent occurrence during the warmer months, tornadoes are relatively rare.

On the west the Plains Province gradually merges into the eastern foothills and slopes of the Rocky Mountains. Here the greater elevations and the topographic irregularities give rise to special climatic features associated with mountain and plateau climates. Colorado has become famous for its health resorts. With a small annual rainfall, light winter precipitation, few storms, little cloudiness, dry, stimulating air, and comparative immunity from many of the sudden and severe weather changes characteristic of the East, there are evident advantages for invalids in this region.

The Plateau Province. The Plateau Province is a great interior region of very diversified topography. It has a wide range of mountain, high plateau, and arid lowland climates, superposed upon and causing local modifications of the general dry continental climate of the province as a whole. "Climatological topography" (Blodget) is here highly significant. The diversity of topography results in a very "patchy" distribution of climates and of vegetation, as local variations of temperature, frost, rainfall, etc., may determine. The winds, also, are largely

topographically controlled, both in the case of the local mountain and valley breezes and of the more general cyclonic wind directions.

The outstanding characteristic is the small rainfall, which, however, shows marked increase with altitude. The higher mountains and plateaus have distinctly more precipitation than the neighboring lowlands. With the exception of local areas in the mountains, the mean annual rainfall is everywhere less than 20 in.; it is mostly below 10 in., and over no insignificant portion of the Southwest it is even below 5 in. The real "American desert" is in southeastern California, southwestern Arizona, and western Nevada. With the high mountain barrier on the west, the whole Plateau district is in the rain-shadow. Arid or semi-arid conditions are to be expected, except where the higher mountains or plateaus give rise to more plentiful precipitation, especially in the north, where general storms occur more frequently and where the barrier is less effective. Even in the south, where the rainfall is less, the higher elevations are fairly well watered. The name of the Aquarius Plateau is a suggestive one. The Rocky Mountains are so far from the Pacific that their rainfall is not as a whole heavy. They are, furthermore, to leeward of the considerable ranges of the Sierra Nevada-Cascades.

Irrigation is made necessary by reason of the deficient rainfall, although dry farming is carried on in certain sections (for example, in eastern Washington) with considerable success. Wherever the streams, supplied by the melting snows and the heavier rainfall of the higher mountains, afford sufficient water, there green oases of varied crops, dotted with fruit and shade trees, break the monotony of the "desert." Most of the winter precipitation is in the form of snow, which is decidedly heavier in the north than in the south, and over the higher elevations than over the lower lands. In the far Southwest snow is rarely seen except on the mountains. Active evaporation in the dry air of this whole interior section is an important factor in causing the snow to disappear rapidly. The rainfall distribution through the year varies greatly in different portions of the district. In the north there is generally a late winter or

early spring maximum. In the south the primary maximum usually comes in late summer, with a secondary maximum in winter. The winter rains and snows are cyclonic. Frequent, often daily, thunderstorm rains are characteristic of the warmer months, especially over the mountains. The rain probability is below 20 per cent, and the minimum number of rainy days in the United States is found in the far Southwest (under thirty).

Temperatures are so largely controlled by the topography that even broad generalization is almost impossible. The conditions over the lower lands may be summarized as follows:

District	Mean Annual	January	July	Absolute Maximum	Absolute Minimum
North	50°	20°–30°	65°–70°	100°–105°	– 10° to – 30°
South	60°–70°	40°–50°+	80°–90°+	110°–115°+	zero to 20°

Minimum temperatures and frost occurrence are mostly a matter of local topographic control and of local air drainage. The dates of first and last frost are very variable. The summers of the southern lowlands are long and intensely hot, but the low humidity is an important factor in making the high temperatures endurable. The southern winters are comparatively mild, dry, and bracing. In the north the heat of the summer is much less severe and the winters are colder. The districts west of the Rocky Mountains are, however, to a great extent protected against severe cold waves of the Eastern type. Dry, stimulating air; an abundance of sunshine; large diurnal ranges of temperature—these are dominant characteristics of the Plateau climates, taken in the large. Diurnal ranges of 40° or more are by no means uncommon. Cool nights follow hot days in summer, especially on the mountains and plateaus. Periodic diurnal, rather than irregular cyclonic, weather types are dominant.

The Plateau Province is beyond the reach of most of the cyclonic storms which so largely control the weather and climate of the rest of the country. At intervals winter storms from the Pacific cross the northern portion of the district on their eastward course along the northern track, and other, but

not greatly frequented, storm tracks cross the central and southern parts. Hence, as a whole, there is a decided lack of sudden, irregular, and severe weather changes. The maximum cyclonic control, here as elsewhere, is in the colder months, but few of the winter storms bring heavy precipitation. Even in winter long spells of fine, bright weather, with light winds, moderately warm days, and cold nights, are common. Summer weather is characteristically fine and settled, broken by afternoon or evening thundershowers and occasionally by the cloud sheet and general rains of a passing summer cyclonic storm.

The Pacific Province. Over the narrow Pacific coastal belt climatic conditions are quite unlike those elsewhere in the country, and in many respects resemble those of northwestern and western Europe, including the Mediterranean area. Blodget gave an excellent brief yet comprehensive climatic comparison when he wrote that "the Pacific coast climates are Norwegian, English and Spanish or Portuguese, with the intermediate France blotted out." [1] The similarity of climates in southern California and in the countries bordering upon the Mediterranean explains the similarity of many of the agricultural products and fruits and of the general methods of cultivation in these two regions. Exposed to the influence of the warm Pacific, with the prevailing westerly winds coming directly from the conservative ocean, and protected on the east by high mountains, the slope as a whole has a modified marine or windward coast climate. A typical west-coast subtropical climate is found in California. The wide range of latitude between north and south, together with the varying topographic controls and the differences of exposure to the ocean influences, explains the great variety of climates which are found in this province. These range from those of the rainy and densely forested slopes of Washington to those of semi-arid southern California; from those of the lowlands to those of the snow-covered mountain tops; from the cool summers of the coast to the hot summers of the great valley. The climate is in general mild and equable, with slight diurnal and seasonal ranges. The relatively small seasonal change is com-

[1] Lorin Blodget, loc. cit.

mon both to the cool and humid climate of the far Northwest and to the warm and dry climate of the southern interior.

The following table summarizes in a very general way the essential temperature characteristics of the Pacific Province, not taking account of the mountainous sections:

District	Mean Annual	January	July	Absolute Maximum	Absolute Minimum
North	50°–55°	35°–40°	60°–65°	90°–100°	10°–0°
South	65° ±	50°	65°–70°	105°–110°	20° ±

The relatively high winter temperatures insure the Pacific coast harbors against freezing, whereas on the northern Atlantic coast ice not infrequently causes difficulty to navigation in severe winters. Further, the mountain barrier of the great Sierra Nevada and Cascade ranges to a large extent keeps out the extremes of winter cold that are found over the interior districts to the east. Under the influence of the warm ocean current eddy which circulates from right to left in the Gulf of Alaska, and of the cool return current which flows along California and Mexico on its way equatorward, the isotherms along the Pacific coast are spread far apart. Hence there are but slight differences of temperature between north and south along the coast, and the rates of temperature decrease per latitude degree from San Diego to Sitka are but 0.95° in January, 0.65° in July, and 0.8° for the year. These temperature gradients may be compared with the much steeper gradients of the Eastern Province, previously referred to. The chart of equal annual ranges of temperature shows clearly how small is the seasonal change of temperature along this coastal strip (not over 25°), whereas across the mountains, in the interior, the ranges reach 40°, 50°, and even 60°. No such severe winter cold waves are experienced here as to the east of the Rocky Mountains, or even over the Plateau. The area over which frost does not occur annually includes southern California. In the region around San Diego, killing frost occurs in less than half the winters. The attractions of outdoor life in southern California have made this locality a favorite winter resort for those who wish to escape the rigors of more severe northern latitudes.

The interior valley of California, between the Coast Range and the Sierra Nevada, being well shut off from the ocean, is very hot, dry, and sunny in summer, especially in the south, while the immediate seacoast is cool, damp, and often foggy. The crowded July isotherms show very clearly the difference between the temperatures of the interior and those of the coast. This is one of the most remarkable contrasts in the world over so restricted an area. The strong diurnal ranges of temperature over the interior valley give relatively cool nights, and the dryness of the air relieves the great heat of the days. The high inland summer temperatures result in the prevalence of cool onshore daytime winds, which are unusually well developed at San Francisco. Sea breezes are a characteristic feature of the whole coast.

The rainfall is heavy (over 100 in.) on the northwestern coast of Washington, and decreases rapidly to the south, to about 10 in. on the extreme southern coast of California, and less than 10 in. in the San Joaquin valley. There is a marked seasonal periodicity. The maximum comes in winter. General cyclonic storms are then most frequent and travel farthest south. The land is colder than the ocean, and the prevailing winds have more of a southerly component. Some southern districts are actually without any rain in summer, and then become very dry and dusty. In the north, however, it rains more or less all through the summer months, although the winter maximum remains. The rainfall migrates from north to south as winter approaches; that is, the rains in the south are distinctly sub-tropical in character and correspond to the winter rains of the Mediterranean districts of Europe. As Woeikof first pointed out, these rains extend farther north in western North America than happens anywhere else in the world.[1] The rains come when the stormy westerly winds are farthest south, and cease when the northward migration of the tropical high pressure belt displaces the storm-bearing westerlies polewards. Even in the so-called rainy season of winter the rains are generally light. They are not steady and continuous, usually lasting but two or three days, and are separated by spells

[1] A. Woeikof, "Die Klimate der Erde" (1887), p. 24.

of fine, sunny weather. On the extreme northwest coast rain falls on nearly half the days in the year. There is a marked decrease in the number of rainy days, as well as in the mean annual rainfall, from north to south. From the point of view of an outdoor life southern California is favored in having very few rainy days. Over the lowlands of the Pacific slope snowfall is of little importance. Even in the north it is very light, and on the coast it becomes practically a negligible factor south of the northern boundary of California. On the mountains, however, even in southern California, snow falls frequently, and on the western slopes of the high Sierras and Cascades it is very heavy. The water supply from these melting mountain snowfields is of supreme importance in irrigating the fertile and productive valleys and lowlands, whose natural water supply, in the form of rainfall, is insufficient for agriculture and for fruit-raising.

The Pacific slope is not subjected to violent weather changes. During the winter a series of general cyclonic storms moves eastward across the northern portion of the province, and occasional storms come in farther south, or their paths carry them south to the more southern latitudes. Hence the northern districts have more rain, more cloud, and more frequent weather changes than the southern. The amount and distribution of the annual rainfall are controlled by the number, intensity, and paths of the winter storms. When these extend farther southward and are better developed, the rainfall is heavier and more widely distributed. In general, rain falls with the cyclonic winds in the southern quadrants, and fair weather prevails with northerly cyclonic winds. The changes in wind direction bring changes of temperature, but since the general temperature gradient is weak and the regions from which the different winds come do not differ greatly in temperature, sudden and marked rises and falls of the thermometer do not occur. In general, southerly to westerly winds are warm in winter and cool in summer, and northerly to easterly winds are cool in winter and warm in summer. The rains of summer, where they occur, are as a rule light and local in character, and fall mostly in the north and on the mountains. The cold-

season precipitation comes in the form of general cyclonic rainy spells. Thunderstorms are infrequent and usually light, and are rarer on the coast and more common inland and on the higher mountains. Special cyclonic winds having certain marked peculiarities occur over some sections, under the combined control of the pressure distribution and of the topography. The northers of the great valley of California have a chinook, or foehn, character. They are dry and dusty and may be injurious to crops. The Santa Ana of southern California is also a hot, dry, and dusty wind, similar to the norther. It blows from northerly or easterly points, and is trying to men and animals. Coming from the dry interior, it reaches the southern coast with the characteristics of a desert wind.

The valley of California is a great agricultural and fruit-raising district, as is the Willamette valley in Oregon. The summer dry season is a favorable climatic feature during harvest time and for drying fruits in the open air. The western slopes of the Sierra Nevada are well watered and forested; the eastern slopes are dry. On the Cascades and on the northern Coast Range there are also abundant forests. North of San Francisco, on the western slope of the Coast Range, are the famous redwood trees; and the "Oregon pine," from farther north, has been known the world over because of its usefulness for ships' masts and spars.

CHAPTER XXI

CLIMATE AND HEALTH

PRESENT VIEWS REGARDING THE RELATIONS OF CLIMATE AND HEALTH · WHAT IS A GOOD CLIMATE? · IS THERE ANY "PERFECT" CLIMATE? · NO CLIMATE IS "THE ONLY CLIMATE" FOR ANY INDIVIDUAL CASE OF ILL-HEALTH · LOCAL VERSUS GENERAL CLIMATES · FACTORS OTHER THAN CLIMATE WHICH DETERMINE THE POPULARITY OF HEALTH RESORTS · THE HEALTH RESORTS OF THE UNITED STATES: GENERAL · THE EASTERN PROVINCE: GENERAL RELATIONS TO HEALTH · THE HEALTH AND PLEASURE RESORTS OF THE EASTERN PROVINCE: GENERAL CLASSIFICATION · SOUTHERN WINTER RESORTS · NORTHERN SUMMER RESORTS · THE GREAT PLAINS · THE WESTERN MOUNTAIN AND PLATEAU REGION · THE PACIFIC COAST

Present Views regarding the Relations of Climate and Health. The modern view as to the part played by climate in relation to health is very different from that held in earlier days. The cause of most diseases was formerly sought directly in atmospheric conditions. These conditions, to state the present view very broadly, are now believed to be important in two ways. They may affect, more or less directly, the life, development, and virulence of the microörganisms which are the specific cause of disease, and they may strengthen or weaken the individual's power of resistance against the attacks of these organisms. The older views concerning the predominant and direct influence of climate have been replaced by the conviction that good hygiene is more important than climate alone. In the matter of the influence of a change of climate as a preventive or restorative, a change of residence, habits, occupation, food, is usually of as much importance as, if not of more importance than, the actual change in atmospheric conditions. If pure air, good food, freedom from worry, time for rest, proper exercise, outdoor life, and a congenial occupation are provided, many bodily and mental ailments yield to the treat-

ment. Climate is by no means to be discarded as of no account. It affects our physical and mental condition and our bodily comfort. It may be dull, rainy, and cheerless, or bright, sunny, and exhilarating. It may tend to keep us indoors or it may naturally tempt us to go out. Thus some climates are naturally avoided; others are sought out. The choice of a suitable climate must depend upon the disease to be dealt with and upon the individual concerned.

What is a Good Climate? What is a "good climate"? This question can here be answered only in the most general way. The answer in individual cases must obviously depend upon a person's physical and mental condition, upon his own personal preferences, and upon the factors other than climate which should be taken into account in each special case. A good climate is naturally one which is favorable to the development of a sturdy race of men and women, physically strong and mentally alert. There is a pretty general agreement among physicians, physiologists, and climatologists that (excepting for those who are distinctly ill) the best climate for most people and most of the time is one which has frequent moderate weather changes, fairly marked annual and diurnal variations in temperature, a reasonable amount of cold during at least part of the year, a refreshing variety in the amount of cloudiness, and sufficient rainfall to provide enough moisture for the growth of grass and crops. Such a climate is an intermediate one. It is neither invariably hot nor permanently cold. It is neither monotonously arid and cloudless nor always dull and rainy. It is between all extremes. The climates of much of the so-called temperate zones are of this general type. Their physiological effects are intermediate between those of the equatorial and those of the polar zones. They exercise the body's power of reaction and adaptation, keeping it physiologically active and in good working condition without subjecting the different organs to too severe a strain.[1]

A climate which encourages people to spend the maximum possible amount of their time outdoors in the open air is, other

[1] F. P. Weber and G. Hinsdale, "A System of Physiologic Therapeutics" (Philadelphia, 1901), Vol. III, p. 18.

things being equal, the best for the majority of men and women. Applying these general principles to the question of health, it may be stated that a health resort is to be recommended where a patient can find comfortable quarters, congenial company, and plenty of diversion, and where favorable climatic conditions, including abundant sunshine and an absence of disagreeable winds and dust and of sudden marked weather changes, encourage an outdoor life. The climate does not necessarily and inevitably cure, but it is very often an important help in the treatment of disease. To quote Sir H. Weber:

> For any given class of cases, that climate is a good one in which the qualities that would be disadvantageous are to a certain degree absent during the whole year, or at least part of the year, while the other qualities are present by the proper use of which the bodily strength is raised and the restoration of the affected organs and functions is facilitated.

Is there any "Perfect" Climate? In the foregoing quotation from one of the leading medical climatologists emphasis is laid on one point concerning which there is a general and persistent misconception. "That climate is a good one," Sir H. Weber wrote, "in which the qualities that would be disadvantageous are to a certain degree absent during the whole year, or at least part of the year." In other words, a good climate has the fewest "outs," or is free from its "outs" during a portion of the year. It is often said that the climate of a certain place is "perfect" or "ideal." As a matter of fact, there is no such thing as a "perfect" climate, anywhere, or all the time. Every climate has some disagreeable features. Health resorts are never equally desirable at all seasons. It is probably safe to say that every climate has advantages of its own for some special purpose, but some climates have more disadvantages, and some have fewer. A southern climate which has a mild and genial winter, and therefore provides abundant opportunities for an outdoor life at that season, is likely to be too hot or rainy or dusty in summer. A northern climate which has the advantages of cool summers is likely to be very cold and stormy and snowy in winter. A western seacoast in sub-tropical lati-

tudes, with the attractions of equable temperatures, mild winters and cool summers, relatively small rainfall and few stormy days, may be too damp and too foggy for many invalids. Mountain resorts, often so useful in the treatment of lung diseases, may have the disadvantages of being too cool at night, too windy and dusty by day, or of having frequent severe local storms. "Perfect" climates, then, do not exist. In climatotherapy, which may be broadly defined as the use of climate for checking or preventing the development of disease and for aiding the recovery of those who are ill or convalescent, the obvious course is to select a locality where the other necessary conditions, such as suitable accommodations, good food, expert medical attendance, and so on, are already provided, and where the climate has a maximum of the desired characteristics for the particular case concerned and the minimum of undesirable features. The seeker after health whose physician orders a change of climate should go away expecting some conditions which are neither perfect nor even altogether agreeable. It should be remembered that any climate recommended by a competent physician doubtless has far more good qualities than bad ones. Advantage can always be taken of the good; the temporary disagreeable ones can usually be escaped by staying indoors. A cheerful disposition which refuses to be overcome by an occurrence of so little importance as an occasional spell of bad weather is always a help.

No Climate is "The Only Climate" for Any Individual Case of Ill-Health. In connection with this misconception regarding the existence of "perfect" climates, there is a widespread and persistent popular impression that certain climates have such special and peculiar properties of their own that there is some one particular climate which is the only one fitted for a special case of illness. If an invalid hits upon this climate, he believes that he will, beyond a doubt, regain his health. Climate, as a recent writer has well put it, may "play an important part in the curative process, but the climate of certain localities does not possess any peculiar properties which act as a specific on certain diseases." Or, as another has put it, "The choice of a climate is not a nerve-racking decision the entire success of

which depends upon hitting upon the one ideal climate in the whole world, but simply the selecting of one out of six or seven localities, any one of which will do all that climate can do to restore health" (Dr. Woods Hutchinson).

Local versus General Climates. The belief that the climates of individual health resorts possess certain special local characteristics of peculiar health-giving value and differ essentially from the general climate of the surrounding country is based upon an exaggerated idea of the importance of local controls over climate. The subject of local as compared with general climates is a large one and cannot here be adequately discussed. A few illustrations may, however, be given to indicate some typical cases.

In the tropics, where cyclonic weather controls are characteristically absent (except in certain restricted areas and at certain special seasons), and where diurnal controls are dominant, a small district well inclosed by mountains probably comes as near to having a local climate as is possible on a land area. Here the general winds, which are the most effective agents in wiping out climatic boundaries, are excluded, and temperature, winds, cloudiness, humidity, rainfall, and other elements are essentially influenced by local conditions. Over most of the temperate zones, on the other hand, where cyclonic cloud and rain areas and cyclonic winds are the characteristic phenomena of the weather and largely determine the character of the climates, local controls inevitably have far less influence. Examples of various degrees of local modifications of climate may be classified under three general heads: (1) extended, open, level plains, lacking bodies of water and forest cover; (2) coasts; (3) mountains. To these may perhaps be added (4) the subordinate and very local influences of forests. In the first-named districts, where the prevailing winds have free sweep, and where there are no local topographic, water, or forest controls, local climates in any real sense cannot exist. In the second case, places on and near the seashore often have the advantage of a cooling sea breeze on hot summer days. The effect of the water is noticed on a much larger scale and to a far greater distance inland when the prevailing winds, or

the temporary cyclonic winds, happen to blow onshore. As waters warm much more slowly than land areas in spring, places situated near the ocean or large bodies of water like the Great Lakes often experience disagreeably chilly onshore winds in that season. These onshore winds are in striking contrast with the warmer winds from the land. Changes in wind direction under these conditions bring marked fluctuations in temperature. The proximity of the ocean or of large inland bodies of water like the Great Lakes may have considerable effects not only upon temperature but also upon cloudiness, humidity, rain, and snowfall. Marine fogs are another local characteristic of some seacoasts. Topography is one of the chief controls in modifying general climates. Elevated stations have certain distinguishing characteristics which, when well developed, give rise to the term "mountain climate." Altitude, as is well known, affects temperature. Mountain stations as a rule have lower temperatures than adjacent valleys and lowlands. On the other hand, on clear, quiet nights, especially in winter, inversions of temperature frequently give slopes and summits distinctly milder spells than those found at lower levels. Mountains and even low hills modify the direction of the winds. A range of mountains, or a single mountain, may protect places to leeward against strong winds. Cool, descending nocturnal breezes, following hot summer days, often provide comfortably refreshing nights where houses are favorably situated opposite the mouths of valleys. Proper choice of building-sites above the level of valley and lowland fogs insures drier air and more sunshine than are found lower down in the fog zone. Mountains offer opportunities for the development of diurnal cumulus clouds on fine summer days, and local showers and thunderstorms occur with greater frequency in mountainous country than over the surrounding lowlands. Forests, although very subordinate controls of local climate, check wind velocity, serving as a protection against disagreeably strong, hot, or cold winds; provide fresh, clean, pure air, very free of dust and of injurious microörganisms; slightly lower the mean temperature and slightly increase the relative humidity. The air in pine forests has long been believed to have certain de-

sirable soothing and healing properties, of benefit in affections of the nose, throat, and lungs. It is upon such local characteristics as those here mentioned, and others like them, that many local weather prognostics and proverbs are based. Familiarity with such weather signs often gives local "weather-wise" people some advantage over an "official" forecaster at a great distance, who has only the general conditions shown on the weather map to guide him.

In these and in other ways general climates may locally be more or less modified. But the larger controls of the general climate persist. What are popularly believed to be special peculiar qualities of the local climates of well-known health resorts are usually in no way essentially different from the climates of hundreds or thousands of square miles of the surrounding country. The factors which are of most consequence in giving such resorts their reputation are not, therefore, the special and peculiar qualities of their local climates, although these may play a part, but the combination of many conditions which render these places safe, desirable, and agreeable residences for invalids and for pleasure-seekers.

Factors Other than Climate which determine the Popularity of Health Resorts. When, centuries ago, Hippocrates wrote "in chronic diseases it is advisable to go to another country," he doubtless had in mind the benefits to be derived not only from a change in climate but also from a change in the general environment, social, mental, and physical. For it cannot be too strongly emphasized that climate is but one element in the treatment, albeit often a, or even the, most important element. In fact, so large a part do the other factors play that it is difficult, even impossible, to determine how much of the benefit of a health resort is derived from the climate and how much from other conditions. Given a suitable climate for the particular illness in question, among the other important contributing factors are accessibility, comfortable and cheerful accommodations, an altered diet of good food, expert medical attendance and proper hygiene, a congenial social environment, outdoor attractions of beautiful scenery, and opportunity for varied forms of exercise and diversion such as walks, drives, sea-

bathing, outdoor sports, and the like. Rest, recreation, freedom from worry, mental and social change and relaxation, usually play an important part in the benefit derived from what is generally called merely a "change of climate," and as a rule accomplish better and quicker results than a more prolonged treatment at home. The use of suitable mineral waters, taken internally or used for bathing-purposes, is another non-climatic element which in the case of some resorts is of predominant importance in the treatment.

The enumeration of these various non-climatic elements should by no means lead to the conclusion that climate is of no value, that there is no such thing as climatotherapy, that climatologists have no concern in this matter. Climate, it is true, is but one element in the treatment, but it is an element of great and, in most cases, of paramount importance. As has already been pointed out, atmospheric conditions are critical in that they affect the microörganisms which are the specific causes of disease, they strengthen or weaken the individual's power of resistance, and they encourage or they discourage rest and recreation out of doors, and outdoors is the best treatment of all.

The established health resorts of the United States and of other countries have gained their reputation because they combine, more or less completely, the complex series of factors just enumerated. They have what has well been termed "the momentum of an early start." Advertising has had, and always will have, a great deal to do with the popularity of all such resorts. So far as climate alone is concerned, there are enormous vacant tracts in this country,—in the Appalachians, in the Rocky Mountains and plateaus, on the Pacific slope,—where health resorts without number could be developed with just as favorable climatic conditions as those which prevail at the resorts already established. But the latter now have the accommodations and the other advantages which are needed to make them popular, and therefore they have the "early start."

In what has thus far been said the term "health resorts" has been exclusively used because the subject under discussion concerns itself primarily with the climatic treatment of disease. It

is, however, obvious that most of the so-called health resorts are also pleasure resorts, frequented by persons who are in no way ill, however much they may sometimes seek to give themselves and others the impression that they are so, but who are attracted by the many natural and artificial advantages which these so-called health resorts offer. There are in reality few places which are frequented solely by invalids. Those which belong in this group are sanitaria where special attention is paid to the treatment of certain special diseases, and where no one is admitted who is not in need of such treatment. Many places which began as health resorts have now become pleasure resorts, pure and simple. Others are rapidly going through the same change. It is therefore impracticable, in the present discussion at any rate, to draw any distinction between resorts which are devoted solely to health purposes and those which are used partly or solely for pleasure.

The Health Resorts of the United States: General. Having now considered in broad outline the larger relations of climatotherapy, attention may next be directed more specifically to the health resorts and pleasure resorts of the United States. This phase of the question is also treated in a very broad way. No attempt is here made to give a catalogue of the health resorts of the United States or to include any numerical or statistical data. All such data can readily be secured from the regular publications of the United States Weather Bureau. All that is here intended is to give a systematic presentation of the larger climatic characteristics, in the form of broad generalization, in such a way that the essential facts may be properly coördinated. Furthermore, it does not fall within the scope of the present discussion to consider in detail the physiological reactions of the human body to varying meteorological conditions, or to mention any but the most common and most familiarly known illnesses.

In what follows, the places which are specifically mentioned by name are considered as types of the health and pleasure resorts which are already established in the same general regions, and may be taken also as representative of many others which may in the future be established in the same districts and with

similar advantages in so far as these concern the climate and the general physical environment.

The Eastern Province : General Relations to Health. From the point of view of health the most important climatic features of the Eastern Province are the great seasonal ranges of temperature, the severe cold of the winters over northern sections being followed by hot summers, and the suddenness, frequency, and amount of the weather changes, especially in winter. With decreasing latitude the southern tier of states has distinctly milder winters, with less and less snowfall, somewhat warmer summers, and generally steadier and more "settled" weather. The Appalachians are of too moderate an elevation to produce typical mountain climates, and the effect of the ocean is reduced to a minimum because the prevailing winds are offshore. Blodget was not far wrong when he wrote, "We scarcely regard the Alleghenies as disturbers of any condition of climate except in the moderate degree produced by altitude alone."[1]

The severe weather changes of the northern winters are usually borne without serious discomfort or harm if the body is in good health and accustomed to adjusting itself quickly. Cold in itself, if not too severe and not too long continued, is beneficial to most people who were born and who have lived in the higher latitudes, for it necessitates increased bodily heat production and metabolism and leads to a beneficial activity of many tissues and organs. On the other hand, these same sudden physiological readjustments may be too severe a strain on the aged and those who, because of illness or general physical disability, cannot react readily. Such meteorological conditions may then bring on various functional disturbances, and are especially harmful in the case of elderly people.

In damp air, evaporation from the internal surfaces of the body is decreased. When the air is at the same time cold, the lungs and respiratory passages not only lose a large number of heat units in the effort to heat the inspired air up to the body temperature, but also lose much moisture by evaporation, warm air having a greater capacity for water vapor than cold air has. These physical processes, and the frequency of the

[1] Lorin Blodget, "Climatology of the United States," 1857.

sudden readjustments necessitated by the variable weather changes, are often followed by certain well-recognized conditions of ill-health. Diseases of the organs of respiration are prevalent in the winter months over the northern and northeastern sections, where the winter cold is often damp, and where temperature and humidity changes are most marked. Such diseases are influenza, bronchitis, catarrh, whooping cough, diphtheria, congestion of the lungs, pneumonia, and so on. The outdoor conditions tend to lower the vitality of the body which is not in good physical condition and, when unusually severe or long continued, may react unfavorably on those who are otherwise in good health. Furthermore, the indoor life which so generally results from the prevalence of cold and of stormy weather, and the consequent lack of fresh air, naturally leads to a general lowering of the vitality and to a diminished power of resistance against the attacks of disease germs. The greatest prevalence of most of the throat and lung diseases toward the end of the winter and in early spring doubtless depends largely upon the fact that the injurious effects of an indoor life, insufficient exercise in the open air, and inadequate ventilation are at a maximum after several weeks or months of that highly artificial "hothouse" sort of life. Diseases of the nervous and circulatory systems and rheumatism are also common in this type of winter climate. In summer hot spells, when both temperature and relative humidity are high, diarrheal disorders become frequent and sunstroke and heat prostrations occur. Hay fever is also a summer condition which affects large numbers of people, who on this account seek places from which the irritating cause is absent.

The Health and Pleasure Resorts of the Eastern Province: General Classification. The simplest rough-and-ready grouping of the health and pleasure resorts of the eastern United States depends upon the fact that the northern winters are cold and stormy, and that the summer temperatures are high, especially in the South. It is thus to be expected that great numbers of invalids, and of others who are in a position to travel, should seek relief from the inclemency of the winter months by going south, and should go north to cooler latitudes during the

hottest season. There is, therefore, a general group of (1) Southern winter resorts, further roughly subdivisible into (*a*) mountain, (*b*) coast, and (*c*) intermediate. Likewise, there is a general group of (2) Northern summer resorts, also subdivisible into (*a*) mountain, (*b*) coast, and (*c*) intermediate. No classification of this sort can be a hard-and-fast one. Many of the Southern resorts which are frequented by Northerners who are trying to escape the cold in winter are used by Southerners who find these same places desirable resorts during the summer. Further, physicians are sending certain classes of cases to Northern resorts, like the Adirondacks, in winter, and it is becoming more and more the habit of some of the younger and more robust members of the population of the northeastern cities to enjoy winter outings in the mountains of New England and in the Adirondacks, where the deep snows give opportunity for winter sports such as snowshoeing, skiing, and tobogganing. Again, a good many readily accessible places in intermediate latitudes, such as Atlantic City, New Jersey, are well filled at all seasons.

Southern Winter Resorts. Southern winter resorts have long been recommended by physicians who realize the advantage of a winter sojourn for many invalids and convalescents in climates where the conditions are less rigorous than those farther north, and are therefore also better suited to an open-air life. The best-known Southern health resorts are in Virginia, the Carolinas, Georgia, and Florida. In midwinter and late winter and in early spring a great exodus of health-seekers, bound south, sets in. Luxurious trains, equipped with every luxury and comfort, with through Pullman cars to all the Southern resorts, are then crowded to their utmost capacity. The development of this elaborate system of transportation, and of the great numbers of modern and highly luxurious Southern hotels, is a natural response to the steepness of the winter poleward temperature gradient on the Atlantic coast.

The invalids who constitute a large element in this annual southward migration are sufferers from tuberculosis, asthma, bronchitis, and other affections of the nose, throat, and lungs; from rheumatism, nervous and kidney troubles, insomnia, and

overwork. Convalescents from acute illnesses of many kinds make up a further considerable percentage of the total. But increasing numbers of those who "go South" in winter are really nothing but pleasure-seekers, afraid of the cold. They belong to the wealthy and semi-leisure classes, and are in search of a soft and comfortable life, with plenty of diversion and such outdoor occupations as golf, sea-bathing, and horse-back-riding. It is, perhaps, fortunate for the future race that so insignificant a part of the population as a whole can afford to bask in the warm sunshine of luxurious Southern winter resorts.

Asheville, North Carolina, is probably the best known of the Southern winter resorts of the mountain group (1, *a*). Far enough south to escape the extreme severity of the winter cold and storms, it is also far enough north to have a moderately stimulating and invigorating climate, with many dry and sunny days. Situated in the midst of a beautiful mountainous country, with excellent hotel accommodations and abundant opportunity for outdoor life and diversion, Asheville has become a resort for those afflicted with pulmonary and similar ailments and for a large group of cases such as nervous disorders, for example, which are benefited by an intermediate climate. It is used by Northerners in winter and by Southerners in summer, the two chief seasons being February and March, and July and August.

The mountainous portions of Virginia, the Carolinas, and Georgia offer essentially similar climatic advantages over enormous areas, and are certain to witness the development of many health and pleasure resorts in addition to those already established. A special class of stations in this same general region is that which has become known on account of its mineral springs; for example, Hot Springs, Virginia, and White Sulphur Springs, West Virginia. These places are chiefly resorted to because of the benefits to be derived from the use of the waters and from the expert medical practitioners whose services are there available, but they also have the advantages of a mild winter climate and excellent accommodations.

The Southern coast resorts (1, *b*) may be considered to extend as far north as Virginia and to include Florida and the Gulf

coast on the south. The New Jersey coast is intermediate between the northern (2, *b*) and southern (1, *b*) coasts, but here again no sharp line of demarcation by latitude can be drawn. Old Point Comfort, Newport News, and Norfolk, Virginia, have long been winter and spring resorts for Northerners and have been used as summer resorts by people from the South. They combine the advantages of a midway location, accessibility, good hotels, and a climate moderated by ocean influences both in winter and in summer. The journey from the great northern cities to the far South being often somewhat trying to those in delicate health, these Virginia coast stations have proved convenient temporary stopping-places and also provide a gradual climatic transition between North and South.

Farther down the Atlantic seaboard the advantages of the southern coast as a place for a winter sojourn naturally increase. Far to the south, at the extreme end of the Atlantic coast temperature-ladder, lies Florida, a deservedly famous winter playground and health resort whose popularity has grown very rapidly. The peninsula of Florida, lying between the warm waters of the Atlantic and the Gulf, in sub-tropical latitudes, enjoys an almost tropical climate, naturally attractive to those who come from the ice and snow of the Northern states. The Florida winters are extraordinarily mild and equable, interrupted now and then by moderate cold spells which, on relatively infrequent occasions, are sufficiently severe to bring frost. Invalids should be prepared for these occasional cold spells, as well as for spells of enervating, even uncomfortable warmth, for there are many distinctly hot and relaxing days, especially in the late winter and spring. Abundant sunshine; a dry, sandy soil; relatively few stormy days; the rare occurrence or complete absence of snow; a soft, balmy air; the beauties of semi-tropical vegetation; every inducement to an outdoor life which natural conditions and the thought and ingenuity of man can devise; excellent train service; luxurious hotels and sea-bathing even in midwinter—these are sufficient to insure the popularity of Florida as a winter resort. Before the heat of later spring begins, a wholesale

exodus of invalids and of pleasure-seekers takes place. The northbound trains are then crowded, most of the hotels are closed, and Florida settles down to the quiet of its long summer. Yet with its trade winds and its sea breezes the summer climate of Florida, especially along the eastern seaboard, is not so wholly undesirable as the majority of the winter visitors believe. This mild, relatively damp climate is soothing and relaxing. It is prophylactic; preventive. While not the best for certain cases and stages of tuberculosis and not unlikely to aggravate certain anæmic conditions, Florida winters have many excellent qualities for convalescents, for elderly persons, for those broken down nervously, for many patients with nose and throat troubles, and in certain diseases of the digestive organs. Too long a sojourn in such a climate may, however, lead to a marked toning-down of the system, to loss of appetite, and to digestive and nervous difficulties. Palm Beach, with its seashore life, is known the country over through persistent newspaper notoriety. Tampa, Miami, Jacksonville, St. Augustine, are familiar names.

The Gulf coast, from northwestern Florida to Texas, by reason of its mild winters and its summers tempered by the prevailing onshore winds, offers numerous resorts which, while not generally frequented by Northerners, are popular among Southerners, both in summer and in winter. New Orleans, about midway on the Gulf coast, attracts Northern visitors, who are diverted by the life of this quaint and picturesque city.

Between the Appalachian Mountains on the west and the Atlantic seaboard on the east, and toward the southern portion of the Atlantic slope, there is an intermediate group of stations (1, *c*) of considerable importance. These are mostly situated at a very moderate elevation above sea level, in a belt of dry, sandy, porous soil covered with extensive pine forests; far enough south to have mild and relatively sunny winters, without the sudden weather changes of the North, yet with a more bracing climate than that of Florida. Aiken and Camden, South Carolina, Pinehurst and Southern Pines, North Carolina, Thomasville and Augusta, Georgia, and other places, with numerous hotels, golf links, and abundant attractions for an

outdoor life, are much resorted to by Northern invalids and pleasure-seekers. The pure, soothing, "balsamic" air of the pine forests is doubtless a health asset whose exact value has yet to be determined.

Northern Summer Resorts. One of the great summer vacation grounds of the United States is New England and the Adirondack area of New York. From the hot and crowded cities vast throngs of people surge northward every summer, by train, steamboat, and automobile, to the mountains, the seashore, and the country, to seek relief from the summer's heat and to find rest and relaxation in beautiful scenery, changed surroundings, and pure air. This annual exodus is chiefly made up of the well-to-do classes, and consists proverbially mostly of women and children. The men are usually obliged to limit their vacations to "week-ends" or to short outings of a few weeks. The large majority of those who frequent these northeastern summer resorts are not invalids in any true sense, but they want and need rest, an outdoor life, and changed surroundings.

The mountain districts of the Northeast—the White Mountains of New Hampshire, the Green Mountains of Vermont, the Berkshire Hills of Massachusetts, the Catskills and Adirondacks of New York (2, *a*)—have long been favorite summer pleasure resorts. The summer population is here many times greater than that of winter. Hotels, boarding-houses, cottages, camps, are filled. These mountain regions have many attractions for the summer visitor. They abound in picturesque scenery. They offer innumerable varied excursions. Mountain climbing, camping, fishing, tennis, golf, appeal to thousands of people.

The specific climatic advantages of the mountains are found in their clean, pure air, in their latitude, and in their elevation. There is relief from the more intense heat of the crowded cities farther south, the nights in the mountains being as a rule cool and refreshing. But during the general hot waves which prevail over large sections of the eastern United States at one time, and import heat from a distance in their southerly winds, the mountains are by no means exempt from high

temperatures. Local topography often plays a considerable part in the special climatic peculiarities of any given mountain resort. A place may be freely exposed to the prevailing summer winds, or it may be shut off from them by a mountain barrier or by forests. There are hot valleys even in the White Mountains of New Hampshire. A favorable location with reference to cool mountain winds may make the difference between a hot and oppressive night and one which provides refreshing sleep.

From the point of view of health many of these mountain districts are famous for their immunity from hay fever and for the benefit which the open-air life gives in many cases of pulmonary and bronchial disorders, in general debility, and in cases of overwork and nervous exhaustion. The early autumn, with its exhilarating days, its crisp, cool, often frosty nights, and the wonderful coloring of its autumn foliage, is the most stimulating and in many ways the most attractive season, but it is a time when most of the summer visitors have already departed to their city homes.

It is unnecessary to enumerate the many well-known resorts of the White Mountains. Good advertising, luxurious accommodations, a "catchy" name—these and other factors may at any time bring into prominence a new hotel, erected in what was before an abandoned forest.

The Catskills, close to New York City, are now almost overcrowded during the hotter months. "The gentle loveliness of a hill country" has made parts of the Berkshire Hills in Massachusetts a veritable garden of beautiful estates. The Green Mountains of Vermont, less rugged than their neighbors, and the White Mountains of New Hampshire are dotted over with peaceful villages and attract a numerous summer population.

Of these northeastern mountain groups the Adirondacks are the most widely known as a health resort, and this chiefly because of the remarkable success which has there been accomplished in the altitude and open-air treatment of tuberculosis. The Adirondack "wilderness" offers many attractions to summer vacationists, with its dense forests, its many sparkling lakes and ponds, its mountain peaks, and its varied inducements to

a healthy, active outdoor life. The pure, dust-free air, the tempered summer heat, the comforts and luxuries of the hotels, the accessibility, combine to give the very name of the Adirondacks a suggestion of enjoyment and peace and, above all, of health. The Adirondacks, like all other places, have their climatic drawbacks. Occasional hot spells, frequent summer afternoon showers and thunderstorms, and nocturnal fogs over and in the immediate vicinity of the lakes and in the valleys are among these. As has already been noted, there is an increasing use of the Adirondacks by those in search of winter outdoor sports. The winters are rough and hard; spells of extreme cold are frequent in the valleys; there are many storms, much cloudiness, and abundant snowfall. But there are also many bright, crisp, exhilarating winter days.

The coast, as well as the mountains, and often to a greater degree, gives relief from the summer's heat (2, *b*). The whole New England seaboard from Mt. Desert on the north to the shores of Connecticut on the south is a succession of summer resorts and of summer cottages. Long Island and then New Jersey extend this line still farther south. With its cool ocean waters, its picturesque and rugged shore line, its numerous bays and rocky islands and good beaches, the New England coast attracts vacationists from many parts of the United States. The Maine coast has exceptionally cool summers, especially to the north. South of Maine follows the short strip of the New Hampshire coast, and then the "North Shore" of Massachusetts, with picturesque Cape Ann, Gloucester, Manchester, and Beverly. A majority of the native population in this whole section gains the chief part of its livelihood from the summer visitors. The general trend of the coast line is such that the prevailing summer winds in many places are tempered by passing over the cool ocean water before they blow onto the land. The sea breeze brings in pure, cool, refreshing ocean air during the noon hours of many summer days. Hence the coast often escapes the extreme heat of the interior and of more southern seashore resorts, which have not the benefit of such cold offshore water as flows along the northern New England coast.

The stimulating and bracing qualities of this cool summer climate have been recommended by the medical profession to many convalescents from chronic illnesses, and to patients suffering from general and nervous debility, anæmia, and in some cases of insomnia. But the frequency of chilling fogs and of damp easterly winds is disadvantageous in most throat and lung troubles, and the climate is too stimulating for many delicate persons who lack the vitality to react properly. These cases do better in a less bracing climate. For them, the "South Shore" of Massachusetts, and the seashore resorts reaching from southern Massachusetts to New Jersey, are generally more favorable. The Massachusetts South Shore, with the Cape Cod and Buzzards Bay resorts, and its warm ocean waters, is warmer, more equable, and more relaxing than the Maine coast. It is therefore better in most cases of insomnia, mental and nervous exhaustion, overwork, and convalescence. Its fogs and dampness are, however, a drawback. Marthas Vineyard and Nantucket, both of them islands to the south of Cape Cod, have even more equable conditions and smaller diurnal temperature ranges than those of the mainland. All their winds blow off the warm ocean water. Rhode Island has its Newport and its Narragansett Pier. Connecticut and Long Island offer many additional seashore residences.

New Jersey may be taken as the southern limit of the Northern summer coast resorts. The coast of New Jersey is practically one long line of health and pleasure resorts. The best known and most consistently and widely advertised of these is Atlantic City, with a long and growing list of luxurious hotels, its famous Board Walk, and its typically American seashore amusements. These attractions, combined with easy accessibility from New York, Boston, Philadelphia, and other large cities, and the excellent bathing facilities, insure the popularity of Atlantic City. In summer hot spells the sea breeze gives welcome relief. And even the offshore winds blow over a narrow stretch of salt water which separates from the mainland the sand bars on which the city is built. Atlantic City has also become a much-frequented winter resort, especially by invalids and by vacation-seekers from the neighboring

cities. There is a general impression that its winter climate is quite different from that of the rest of this part of the country. This is a mistake. The New Jersey coast is still within the storm control of the northeastern United States. It has winter rains and snow, cold waves, much cloudiness, and frequent temperature changes. Its easterly winds are damp and chilly. On the other hand, however, the very rapid poleward temperature gradient along the Atlantic coast in winter gives New Jersey the advantage of mean winter temperatures somewhat higher than those farther north. Owing to the latitude and the location, immediately on the ocean, the snowfall is less than inland or in higher latitudes. The sandy soil dries quickly and warms rapidly, so that the snow which falls does not remain long on the ground. Bright, fine winter days show a considerable degree of diurnal warming.

It should be remembered that a large part of the reputation of Atlantic City and of many other places rests upon artificial conditions. In the case of Atlantic City itself, most of the Board Walk is sheltered from the northwest winds. On cold or stormy days people stay indoors, perhaps shutting themselves up in glass-inclosed sun parlors; venture out on the Board Walk in covered wheel-chairs, or sit and walk in sheltered places. Being away from home and having no duties which call them outdoors, no matter how inclement the weather they are naturally more or less unconscious of what the weather is. Advantage is taken of being out and of enjoying the warm sunshine and tonic air on all fine days. As so often happens, the change which benefits is more the rest, the freedom from worry, and the new and, to most people, diverting surroundings, than any marked difference in climate. As a winter and early spring health resort the New Jersey coast is recommended for those who are suffering from overwork, insomnia, or throat troubles, for convalescents from acute diseases, for many elderly people and those whose vitality is lowered—for all of whom comfortable accommodations, good food, pleasant surroundings, and somewhat less strenuous physiological adjustments to severe weather changes are desirable. Lakewood, New Jersey, although not on the immediate coast, may also receive men-

tion here. Situated on the dry sandy soil of the pine belt of New Jersey, with somewhat warmer and more genial winters than prevail farther north, with clean, dust-free air, and with protection against the coldest winds, Lakewood was formerly a health resort, but has now become largely a winter pleasure resort.

The third group of Northern summer resorts is in the interior —neither in the mountains nor on the seashore—and may be classed as intermediate (2, *c*). Here come the Maine woods and Rangeley and other lakes in Maine and the Lake Champlain and Lake George districts. Beautiful and varied scenery, extended forests, relatively cool, stimulating summers, and the opportunity for camping and fishing and for living a simple outdoor life have brought to many thousands of mentally and physically tired city folk rest and relief and fitness for their winter's work. For sufferers from hay fever and for many persons for whom the northern seacoast is too damp and too stimulating these intermediate stations have proved highly beneficial.

The Great Plains. The Great Plains constitute a natural and logical province from the viewpoint of climate alone; but on account of their broad expanse of remarkably uniform topography, the similarity of their general climatic characteristics, and the lack of local scenic attractions, they have not developed climatic health resorts in the strict sense of the term.

The Western Mountain and Plateau Region. The great mountain and plateau region of the West, extending from the eastern foothills of the Rocky Mountains to the Cascade-Sierra Nevada divide, has altitudes sufficiently great to give true mountain climates, with their special features of strong sunshine, dry air, and marked diurnal ranges of temperature. Combined, as they are in the western United States, with a small annual rainfall, comparatively few general storms, and little cloud and fog, such climates have distinct advantages for many invalids. Furthermore, with a great variety of topography and of altitude—lofty mountains, elevated plateaus, deep valleys, low-lying deserts—this great Western region embraces a wide variety of local climates. Colorado has become famous the world over for the success which has there resulted from the

altitude treatment of pulmonary tuberculosis. As Dr. C. Theodore Williams expressed it, "The favorable results [of the climate] . . . may be seen in the large number of former consumptives whom it has rescued from the life of invalidism and converted into healthy and active workers."[1] The development of the muscles of the organs of respiration; the resulting expansion of chest and lungs; improved circulation; increased heat production; better appetite; a general stimulation of various organic functions — these are among the effects of the altitude cure which are helpful in raising the vitality and in giving the body the power to overcome the ravages of the tubercle bacilli. There are, however, a good many classes of tubercular cases for whom considerable altitudes are too stimulating, or even distinctly injurious, and who do better nearer sea-level, where there is less danger of overworking the heart and blood vessels. Such cases are those of elderly patients, those with diminished vital powers, and those suffering from insomnia or from cardiac and bronchial affections. The winters of Colorado are marked by an abundance of fine, crisp, sunny days and little snowfall except on the higher mountain slopes, where it accumulates to great depths. Lower down snow falls much less frequently, melts rapidly, and offers no serious obstacle to an open-air life. The summers have warm days and cool nights, with frequent local showers and thunderstorms in the mountains. In the foothills region the high dusty winds of the warmer months are a drawback. As compared with the northern tier of states, especially in the eastern part of the country, there are in Colorado few general storms, even in winter. The winter's cold and the heat of the summer days are much more easily borne in the dry mountain air than is the case with the same temperatures in the more humid East. The large diurnal ranges of temperature usually insure refreshingly cool summer nights and relatively warm winter days. Invalids can as a rule be out of doors for several hours a day, even in midwinter, and need only light wraps in the strong sunshine. The western mountains are so far from the great eastern centers of population

[1] C. T. Williams, "The High Altitudes of Colorado and Their Climates," *Quart. Journ. Roy. Met. Soc.*, Vol. 19 (1893), pp. 65–82.

that they have not in the past attracted such great numbers of summer vacationists as frequent the mountains and seacoast of the northeastern sections. But those who are in search of an outdoor life in a rugged country of great scenic beauty are going to Colorado in larger numbers each year, and the regular tourist travel to the Yellowstone and Glacier National Parks and to other favored districts of great natural wonder and beauty is increasing annually.

What was called by the late Dr. S. E. Solly the Invalid Belt of Colorado varies in altitude from 4500 to 8000 feet and extends from Middle and Estes Parks to Colorado Springs. The latter is perhaps the best known of all the Colorado health resorts, especially for those predisposed to, or afflicted with, tuberculosis of the lungs. A considerable part of the population of Denver has settled there for reasons of health. Manitou Springs is another health resort. The climate of the region which these cities represent is also favorable to other classes of cases which need an open-air life and not too great a stimulation of various bodily functions. At these and other places in the Invalid Belt, special attention is paid to the care of consumptives. Expert medical practitioners who are skilled in the treatment of tuberculosis are available. Excellent accommodations are provided. Everything has been done to aid the cure, for the accomplishment of which the high, dry, sunny climate of Colorado has proved to be so peculiarly well adapted.

The so-called "Parks" lie west of the Colorado Front Range. They are sheltered intermontane basins or valleys of from 6000 to 8000 feet altitude, with scattering pine-tree growth, of a park-like character which gives them their name. Some of these parks are well-frequented summer resorts.

South and southwest of Colorado come the mountains and plateaus and valleys of New Mexico and Arizona and then, along the southern border of the United States, the low-lying deserts and irrigated valleys of the driest portion of the country. It is highly significant that well south of Colorado, in the highlands of New Mexico, at Fort Bayard and at Fort Stanton, the United States government has established its consumptive

sanatoria for the army and navy.[1] Of this general region Dr. W. A. Hammond, formerly Surgeon-General of the Army, wrote, "New Mexico is by far the most favorable residence in the United States for those predisposed to or afflicted with phthisis"; and Dr. W. M. Yandell of El Paso has said that if a mild climate during the cold season is desired, New Mexico and Arizona south of latitude 35° furnish by far the best winter climate in the United States for consumptives.[2] Northern New Mexico and Arizona have very much the same climatic advantages as has Colorado for the altitude treatment of tuberculosis, but are even less subject to cyclonic weather changes by reason of their somewhat lower latitude. Their winters are also milder for the same reason, but occasional spells of extreme cold and snowstorms are to be expected at the higher levels. The early mornings and evenings are usually frosty; the noon hours are warm and bright. The tonic, invigorating quality of the dry, sterile air; the enjoyment and encouragement which come from an abundance of bright sunshine; the very small winter precipitation, with a minimum of rainy and cloudy days; the possibility of open-air treatment throughout the cold season; the wonderful and varied coloring of the mountains; the glories, the bigness, and the appeal of the desert—these are among the attractions of the great Southwest. The summers are long and hot and too debilitating for many invalids. The mountains then have an advantage over the lowlands, owing to their more comfortable nights, due to the marked diurnal variation in temperature and often to the occurrence of cool mountain breezes. On the desert lowlands of the south the summer heat is more intense and lasts longer. The dryness of the air, however, helps to make these very high temperatures endurable. A distinct drawback to a summer sojourn in most parts of the semi-arid Southwest, especially on the low-lying plains, is the frequency of high, dusty winds. In many places this dust is alkaline and is very irritating to the

[1] Since June 15, 1920, the hospital at Fort Bayard has been in charge of the United States Public Health Service, and is now known as "Hospital No. 55, Fort Bayard." The hospital at Fort Stanton is "United States Marine Hospital No. 9." There is also a United States Naval Hospital at Fort Lyon, Colorado.

[2] Quoted by Solly, loc. cit., p. 276.

mucous membranes. As health resorts such localities are obviously undesirable, if not altogether impossible.

While fully recognizing the many remarkable cures which have been accomplished in the cases of thousands of tuberculous patients when such persons were sent out in time, were properly advised as to the best place of residence, and were financially able to make the best possible use of their opportunities, it is undeniable that many serious mistakes have been made by the medical profession in advising invalids to go to the Southwest. Such mistakes arose largely from an inadequate knowledge of the actual climatic conditions. Patients have been sent out to the wrong places and at the wrong seasons. Invalids, far advanced in the later stages of tuberculosis, have been advised to take the long journey when they were in no condition to stand the fatigue and could not afford the expense. Many have gone to the higher stations, ill prepared for the cold of winter, or to the southern towns during the intense heat of summer. It is manifestly unfair to attribute the deaths of many unfortunate invalids to climate, when such persons came too late and had improper care and surroundings. It is as true today as it was when Blodget stated it, that "large numbers seek milder climates and perish there, whose cases should be set down to the country from which they came."[1] A difficulty in the use of New Mexico and Arizona for purposes of health lies in the fact that there are as yet comparatively few places in which adequate provision is made for invalids. As a health resort the Southwest is by no means fully developed. Santa Fé, Las Vegas, Albuquerque, in New Mexico (5000–7000 feet), are fairly typical and are used as all-the-year-round health resorts for certain classes of lung cases. In Arizona representative stations are Phoenix, at a low altitude, and Prescott and Flagstaff, at greater elevations. El Paso, in extreme western Texas, has similar conditions to those of southeastern New Mexico at the corresponding altitudes. It also offers a favorable climate for invalids in winter, but the long summers are hot.

The Pacific Coast. For many centuries the Mediterranean climates of the Old World have been lauded in song and in

[1] Lorin Blodget, loc. cit.

story. For generations the Riviera has been a favorite resort where invalids have sought health, and where an escape from the rigors of a cold and inclement winter has been found by those who have had the time and the means to leave their northern homes. The sub-tropical belt, which has its greatest extension in the classic Mediterranean region, combines many of the qualities which taken together probably make as nearly "ideal" a climate for the majority of people as can be found. Situated far enough from the equator to be spared continuously high and enervating temperatures, yet near enough to it to escape the extreme cold of higher latitudes, these transitional sub-tropical belts are highly favored. With prevailing fair skies and abundant sunshine during most of the year, equable temperatures, and generally moderate winter rains, Mediterranean climates, as they have come to be called, possess many advantages which fit them to be health resorts. The long list of European resorts stretching along the shores of the Mediterranean Sea, in Italy, France, Spain, and Africa, bears abundant witness to this fact. In the United States southern California, with similar climatic controls and characteristics, ranks high in the estimation of the medical profession and in the minds of countless thousands who, in good health, have there sought and found pleasure and relaxation.

The Pacific slope, with its great latitudinal extension, its snow-capped mountains, and its broad and fertile valleys, embraces a great variety of climates. The advantages of the equable climate of the Puget Sound region and of other portions of the north Pacific slope, with their generally mild winters, cool nights even in midsummer, and opportunities for outdoor life, are attracting increasing numbers of tourists as well as of permanent settlers. There is much to support the somewhat extravagant enthusiasm in regard to their climate which is a characteristic of the people of this section. It is, however, the southern coast of California which is still the best-known health resort, and it is therefore to that district that this discussion especially relates. A conservative estimate would indicate that fully three fourths of the Eastern visitors to southern California find their attraction in its climate and in the outdoor life which

that climate makes possible, in the midst of vineyards and orange groves and gardens of roses. The luxurious hotels make every possible provision for visitors, and the social intercourse with people from all over the country is an added element of attraction for many. The essential features of the climate from the standpoint of health are its mildness and equability, without enervating qualities; the relatively mild winters and cool summers; the short winter rainy season, without snowfall and with rare frosts; the absence of sudden and extreme weather changes. Even in the so-called rainy season of winter the rains are light; they are not steady and continuous, but usually last only two or three days at a time and are separated by much longer spells of fine sunny weather. The mountain barrier of the great Sierra Nevada and Cascade ranges keeps out the extremes of winter cold which are found over the interior districts to the east of the mountains. In the dry season of summer, mild and nearly continuously fine weather is the rule. At this season the California Sierras, including the foothills, with their lower temperatures and other local climatic advantages, offer many attractions to seekers of health and pleasure.

Southern California has an all-the-year-round climate. It is frequented at all times. Winter and spring, however, are the favorite seasons. It is then that the attractions of outdoor life are most appealing: the vegetation is green and fresh, and the great throng of visitors from the northern and eastern parts of the country, escaping from the severe winters of the interior and the Atlantic slope, take the long overland journey in order to be warmed by the California sunshine, to enjoy sea-bathing, and to revel in a tempered climate where fruits and flowers and green leaves replace the bare trees and frozen ground of the East. Even the most enthusiastic native of the Pacific slope must be satisfied with Blodget's reference to "the elastic atmosphere and bracing effect" which "constitute a striking difference from those of the Eastern states." There is no climate on the coast "which is not the reverse of enervating. . . . All residents concur in pronouncing it more favorable to physical and mental activity than any other they have known, from whatever quarter they come."

The health district of southern California lies south of latitude 35° N. and is separated from the interior by mountains which border the coast. It is a country of fertile valley and plain. San Diego, Coronado Beach, Santa Barbara, Los Angeles, Pasadena, are names as familiar as San Remo, Nice, Mentone, and Monte Carlo. Most of the resorts are on or close to the coast, and at a low altitude. They have advantages on that account, and some disadvantages. The special topographic surroundings of each station contribute something toward giving it certain local characteristics, but in the main the climatic conditions are everywhere similar. On the immediate coast the special features are the fog, the dampness, and the prevalence of cool onshore breezes. The fogs are chiefly nocturnal and spring and summer phenomena. The diurnal onshore breeze from the cool Pacific waters is of great help in tempering the heat of summer, but brings a chill which is trying to many delicate persons and demands the protection of warmer clothing than the majority of visitors, unfamiliar with the details of the local climates, at first think necessary. The high relative humidity, resulting from the proximity to the sea, the fog, and the onshore winds, is a feature which is often surprising to newcomers. It is a prevalent idea, even in the minds of many experienced medical practitioners, that the small annual rainfall, which, so far as actual precipitation is concerned, insures a "dry" climate, is necessarily accompanied by a low degree of humidity. The late Dr. S. E. Solly expressed the following opinion: "This Pacific coast climate is damp and presents its claims to sufferers on the grounds of equable temperatures and sunshine. It lacks the dry air and tonic, stimulating qualities of the elevated inland plains, but offers less shock to the system from rapid changes."[1] And again: "It should be thoroughly understood by the Eastern visitor in search of health that if he seeks more days of sunshine and opportunities for outdoor life, with an equable temperature and an average humidity a little greater than that of New York or Boston, he can find what he desires at Santa Barbara or San Diego." The damp, cool night air on the coast, not infre-

[1] S. E. Solly, loc. cit.

quently combined with fog, is thus a climatic feature which is not to be ignored in the treatment of invalids. Such persons can, of course, to a certain extent escape this condition by remaining indoors at night.

In climatotherapy southern California has in the past been much used for tubercular cases, for many cardiac affections, for insomnia, for nervous disorders, and for persons of somewhat lowered vitality. For many invalids, especially those with throat and lung troubles, the "back country," among the hills, offers more suitable conditions than the damper, chillier, and more trying seacoast. Redlands and Riverside are representative of the interior district, somewhat back from the coast and at higher elevations than the stations directly on the ocean.

CHAPTER XXII

CLIMATE AND CROPS[1]

INTRODUCTION · AGRICULTURAL REGIONS OF THE UNITED STATES · CORN · HAY, FORAGE, AND PASTURE · COTTON · WHEAT · OATS, BARLEY, AND RYE · TOBACCO · POTATOES AND OTHER VEGETABLES, AND TRUCK-FARMING · FRUITS · LIVE STOCK · DAIRYING · THE SUB-TROPICAL COAST AGRICULTURAL REGION · DRY FARMING · IRRIGATION · FORESTS · CROPS AND BUSINESS

Introduction. With their wide range of climatic types and their great variety of vegetable products the United States offer an unusually interesting field for the study of the relations between climate and crops. In the present discussion attention is directed only to the larger and most obvious of these relations and to a few of the more important crops. The details belong to the agricultural meteorologist, whose interest is in the more intricate controls which seasonal weather exercises over the quality and the quantity of the crops. Climate is but one of the many controls which determine the present geographical distribution of the staple crops, but it is fundamental. Soil, the kind of seed, methods of cultivation, population, transportation, and other factors play a part in a relation which is inevitably so highly complex that great caution is necessary in the endeavor to express it in terms of one or more of the climatic elements. Moreover, the present boundaries of the larger crop zones are not rigidly fixed. The introduction, by importation or by local production, of new varieties of cereals, fruits, and grasses; more extended irrigation; improved means of transportation; changing economic conditions, as of labor or com-

[1] The article upon which this chapter is based was originally printed in *Quart. Journ. Roy. Met. Soc.*, Vol. 45 (1919), pp. 1–18. Permission to reprint, with or without changes, was very kindly given by the Council of the Royal Meteorological Society.

petition with another crop,—these and other varying controls constantly bring about readjustments.

The number of publications on various relations between climate and weather and crops is large and is increasing rapidly.[1] The essential facts regarding the major geographic and climatic controls of crop distribution are clearly and authoritatively stated in "A Graphic Summary of American Agriculture," and in the "Geography of the World's Agriculture," issued by the United States Department of Agriculture.[2] In the following pages the statements concerning the geographic controls of agriculture in the United States have been taken freely and directly from these two publications, which supersede earlier, less complete, and less accurate charts and discussions.

[1] For government publications available for distribution see Price Lists 16 (Farmers' Bulletins, etc.), 42 (Irrigation), 44 (Plants), and 48 (Weather, Astronomy, and Meteorology), which may be secured, free of charge, from the Superintendent of Documents, Washington, D.C. See also J. W. Smith, "Agricultural Meteorology," 1920 (the first American textbook on the subject; an excellent summary by the chief American investigator in this field; contains an extensive bibliography and is invaluable for study and reference). Among the publications which have appeared since the date of Professor Smith's book, the following may be cited: O. E. Baker, "The Agriculture of the Great Plains," *Annals Assoc. Amer. Geogr.*, Vol. 13 (1923), No. 3, pp. 110–167; A. P. Brigham, "Environment in the History of American Agriculture," *Journ. Geogr.*, Vol. 21 (1922), pp. 41–49; J. B. Kincer, "Computing the Cotton Crop from Weather Records and Ginning Reports," *M.W.R.*, Vol. 49 (1921), pp. 295–299; "The Climate of the Great Plains," *Annals Assoc. Amer. Geogr.*, Vol. 13 (1923), No. 2, pp. 67–80; "The Cotton Plant in Relation to Temperature and Rainfall," *M.W.R.*, Vol. 52 (1924), pp. 306–307; "The Adjustment of Agriculture to Climate, Soil Condition and Topography," *U. S. Dept. of Agric. Yearbook for 1924*; "Influence of Weather on Farm Work and Crop Yields," ibid.; B. E. Livingston and Forrest Shreve, "The Distribution of Vegetation in the United States, as Related to Climatic Conditions," *Carnegie Inst. Publ. No. 284*, 1921; Franz Termer, "Wetterschäden und Landwirtschaft in den Vereinigten Staaten von Amerika" (*Studien über Amerika und Spanien, No. 1*), Halle a. Saale, 1923, 79 pages; A. B. Waller, "The Relation of Plant Succession to Crop Production," *Ohio State Univ. Bull.*, Vol. 25, No. 9, January 20, 1921 (*Contributions in Botany, No. 117*); L. C. Gray and others, "The Utilization of Our Lands for Crops, Pasture and Forests," *U. S. Dept of Agric. Yearbook for 1923*, pp. 415–506; Precipitation and Humidity section of *Atlas of American Agriculture*, especially pp. 37 and 40.

[2] O. E. Baker, "A Graphic Summary of American Agriculture, Based Largely on the Census of 1920," *U. S. Dept. of Agric. Yearbook for 1921*; Separate No. 878, 101 pages. The *Yearbooks* for 1921, 1922, and 1923 are devoted largely to the discussion of the geography of production and distribution of the more important crops and kinds of live stock. See also V. C. Finch and O. E. Baker, "Geography of the World's Agriculture," *U. S. Dept. of Agric., Contribution from Office of Farm Management*, 1917, 149 pages, 206 figures.

Agricultural Regions of the United States. Some simple scheme of subdivision into agricultural districts or belts is necessary to serve as a framework into which the larger facts of climate and crop distribution and of types of farming may be fitted. Only thus are a rational understanding, easy memorizing, and proper coördination of scientific results possible. A convenient and logical map suggested by O. E. Baker is here adopted as an authoritative, simple, and satisfactory basis for the present discussion (Fig. 145).[1] The brief text accompanying this map, and also an unpublished manuscript on the climatic control of the types of farming in the United States, by W. G. Reed (formerly Major, Signal Corps, U. S. A.), have been freely drawn upon.

This map is based primarily upon the distribution of the principal crops and upon the types of farming. The country is conveniently divided into two major divisions, separated by a transition zone lying in a general way along the 100th meridian. In this zone the mean annual precipitation increases from about 15 in. in the extreme north to 25 in. in southern Texas. In this southern section the rainfall is more torrential in character, and evaporation is much greater than in the north. It should, however, be remembered that in addition to the annual amount of precipitation the season of maximum rainfall, as well as the character and duration of individual rainfalls, is a critical factor in the relation of climate and crops. The eastern half of the country has sufficient rain in normal years and produces crops cultivated by ordinary farming methods. It is characterized by tilled crops, small grain, and tame hay and pasture. The western half, with generally inadequate rainfall (except on the north Pacific coast and in parts of California and of the northern Rocky Mountain district), contains only limited areas where ordinary farming of the eastern type can be practiced. The West is essentially a region of irrigation, of dry farming, of wild hay, and of grazing. Ordinary humid farming of the eastern type is found only in limited areas. Both eastern and western halves are subdivided into six agricultural

[1] O. E. Baker, loc. cit. in footnote 2, page 473. Fig. 2, on page 10, is here reproduced as Fig. 145.

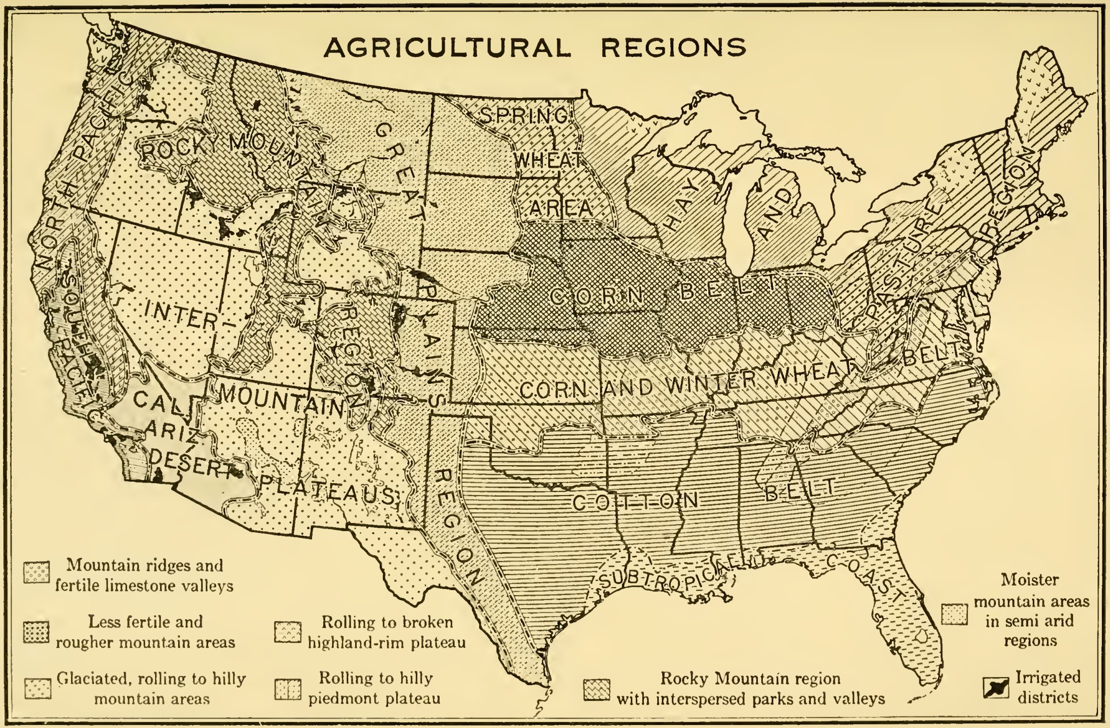

FIG. 145. Agricultural Regions

provinces. Each of these is distinguished by certain more or less distinct combinations of crops or systems of farming resulting chiefly from the differing climatic conditions. The eastern half is essentially a lowland, interrupted toward its eastern margin by the plateaus and mountains of the Appalachian system, all of moderate elevation. Hence latitude (that is, temperature) and not altitude is the dominant climatic control. The agricultural provinces therefore have a general east-and-west extension and, with one exception, are given crop names.[1]

West of the Great Plains, on the other hand, the topography is very varied, with high mountain ranges extending in a general north-and-south direction. The agricultural provinces also extend roughly north and south. Rainfall and topography are here the critical factors. Under the control of the varying conditions of rainfall, temperature, altitude, soil, and economic factors the crops in this western section are very varied and often extremely localized. There are no great belts distinguished by certain dominant crops as in the East. A detailed map of crop distribution in the West is therefore very "patchy," the patches usually corresponding to districts of local irrigation. The names of the agricultural provinces in the West are not derived from the characteristic crops, but from location or topography.

The "sub-tropical coast" belt is so named because the type of agriculture varies so much in different sections that no single crop can be selected as best fitted to give a designation to the belt. Rice-farming, winter-vegetable production, the growing of sugar cane, cattle-ranching, and citrus-fruit orcharding are all found there.

Corn. Corn is the leading and the most typical American crop. The United States produce about three fifths of the world's supply. It is dominant in the corn belt, and is also of great importance in the corn and winter wheat region and in the cotton belt. In the latter it is the all-important cereal. The climate and soil of the corn belt are, however, peculiarly suited to this crop. The area of maximum production is limited

[1] Note, however, the effect of the Appalachians.

by a mean summer temperature of 70°–80° F., a mean night temperature exceeding 58° F., an average growing (frostless) season of about five months (one hundred and fifty days), and an annual rainfall of 25–50 in. or more. Nearly all the corn is south of the mean summer isotherm of 66° and of a line showing a mean night temperature, during the summer months, of 55°. Because of its temperature requirements, corn cannot be profitably cultivated far north or at considerable altitudes in the West. Extended corn cultivation is fairly well limited in the West by the mean summer rainfall line of 8 in.; but if the summer temperature is over 70°, and evaporation is not excessive, an even smaller summer rainfall will suffice. The heat and moisture requirements of different varieties of corn vary greatly. Some southern varieties need a frostless season of six months (one hundred and eighty days) and a mean summer temperature over 80° F. Corn needs more water in the South, where evaporation is greater, than in the North. In the West as a whole the rainfall is too light and the nights are too cool for corn, but the crop does well in the warmer Pacific slope valleys and in parts of Arizona and New Mexico.

Nearly all the southern corn supplies are used locally in the form of "hog, hominy, and hoecake." Elsewhere only a little corn is used directly as food by man: most of it is converted into beef, pork, or horseflesh. It has been estimated that one pound of American beef represents about ten to twelve pounds of corn, and one pound of pork about five to six pounds. In the form of beef much corn is shipped abroad. Where the growing season is too short or the temperature too low for maturity, corn is widely grown for silage. The summer rainfall, however, must be about 7 in. or more. Corn is a profitable crop and therefore tends to become dominant in regions where the climate is best suited to it, especially if the competing crops require farm labor at the same time. Corn is widely grown in the cotton belt. The climatic range of cotton, however, is much more limited than that of corn, and as cotton is a more profitable crop, corn there becomes subordinate.

The selection of drought-resisting varieties and of improved methods of cultivation is making it possible to extend the

limits of corn production westward, into districts of greater aridity. The cultivation of corn in districts of deficient rainfall is "largely a matter of taking chances with seasonal conditions," but there are certain controllable conditions, such as seed and soil, which often determine the success or failure of the crop.[1] It has been pointed out by G. N. Collins that the pioneer work of the Hopis and Navajos along agricultural lines has not been sufficiently appreciated, and that many of the facts which modern white men have ascertained by laborious experiment might have been learned by studying the agricultural practices of the American Indian.[2] From prehistoric times the Southwestern agricultural Indians have raised corn successfully in regions where drought, and especially the absence of spring rains, render impossible the growth of many of the common varieties of Indian corn. The peculiar features of the corn used by these Indians are (1) a greatly elongated mesocotyl, which permits deep planting, and (2) the development of a single large radicle, which descends rapidly to the moist subsoil and supplies water during the critical seedling stage.

Hay, Forage, and Pasture. The hay, forage, and pasture crops are very widely distributed, for winter cold or insufficient rainfall necessitates a supply of forage in all sections except the Gulf and the north Pacific coasts, and their many different varieties are adapted to a wide range of climates. In the hay and pasture region one half or more of the improved land in nearly every county is occupied by the crops which give the name to the belt. The summers are moderately cool (mean below 70°), and the rainfall is fairly abundant (over 30 in.). The extended cultivation of other crops is limited by the cool summers and also, in some sections, by unfavorable soil and rugged topography. The dense population has led to the development of the dairy industry, with the resulting demand for pasture grass in summer and for hay in the long, severe winters. Critical climatic factors in the outdoor curing of hay are the occurrence of dry spells of several days' duration while

[1] C. P. Hartley and L. L. Zook, "Corn-Growing under Droughty Conditions," *U. S. Dept. Agric., Farm. Bull. 673*, 1916.

[2] G. N. Collins, "Pueblo Indian Maize Breeding," *Journ. Heredity*, Vol. 5, June, 1914.

the grass is being cut, as well as sufficient summer rainfall to produce good grass. These conditions are as a rule found in the hay and pasture region. Furthermore, hay is bulky and expensive to ship, and hence is best produced in the region where there is the greatest demand for it.

Timothy and clover are the chief eastern hay crops, and corn is widely grown for silage. The southern boundary of timothy is fairly close to the mean summer isotherm of 77° and the limit of two hundred days in the growing season. Cotton pays better than hay in the South. In addition, the high humidity and the short dry spells of summer are not favorable for the curing process, and the lack of a large beef and dairy industry hitherto has removed the demand for grass and hay which exists in the North.

Over the Great Plains the natural grasses once fed vast herds of bison and later furnished abundant outdoor pasturage the year round for live stock. Stock-raising grew rapidly into a very important industry. Overstocking and partial exhaustion of the natural forage resulted in great losses of cattle during dry seasons and in the severe winter cold and storms. It gradually became clear that in many sections immense herds of cattle, roaming more or less at will and suffering heavy losses, were becoming less profitable than smaller herds, kept and bred under more careful supervision and provided with some forage in addition to that supplied only by the natural range. Alfalfa, sorghum, and other forage crops were planted, and hay meadows fenced in. Local irrigation led to the development of small farms, with intensive cultivation of many general farm crops. The great cattle ranches of wealthy owners or of corporations have become less numerous, and the smaller holdings of individual farmers who combine stock-raising with the growing of varied crops and of feed for the cattle have increased. The whole question of the selection of the most suitable grasses and forage plants for use in the West has thus become of great importance.[1]

[1] T. A. Williams, "A Report on the Grasses and Forage Plants and Forage Conditions of the Eastern Rocky Mountain Region," *U. S. Dept. Agric. Div. Agrost., Bull. 12*, 1898. See also C. V. Piper and others, "Our Forage Resources," *U. S. Dept. of Agric. Yearbook for 1923*, pp. 311–414.

Hay is the leading crop of the West. Western hay in the form of beef or of wool is shipped in a highly concentrated and profitable form. The actual acreage of hay and forage in the West cannot be very large for the reason that deficient water supply or poor soils are limiting controls. Throughout most of the West hay is an irrigated crop. As irrigation is expensive, the return must be large in order to be profitable. Alfalfa is the logical western hay crop (especially in the Rocky Mountain and arid intermountain regions) because, as pointed out by W. G. Reed and others, it has certain obvious advantages over timothy, clover, or other similar crops. Alfalfa has long roots, which make it drought-resistant. It gives several cuttings a year, whereas timothy and clover give only one or two. About half the alfalfa raised in the United States is irrigated. Where alfalfa is not cultivated, hay is obtained from native grasses or small grains. Although alfalfa is grown under a great variety of conditions, it does best where the summers are not rainy, and in the Southwest. Very little of it yet comes from east of the Mississippi, but its cultivation there is increasing. Since it requires more time for drying than either timothy or clover, the longer dry spells of the West are much more favorable for curing it than are the shorter rainless spells of the eastern summers. Moreover, alfalfa in the East requires labor at a time when corn also needs it, and the ordinary varieties of alfalfa are often killed by the cold eastern winters. Further, timothy and clover fit better into the eastern system of crop rotation. Taking the agricultural provinces of the West individually, wild grasses are the leading hay crop over the Great Plains; small grains, cut green, on the Pacific coast; alfalfa, in the Rocky Mountain and arid intermountain regions.

Kafir corn and milo maize have excellent drought-resisting qualities and have therefore become important crops over the southern Great Plains. They are used both for grain and for forage. The bulk of the crop is within the rainfall lines of 15 and 30 in. The northern limit of Kafir is the mean summer isotherm of about 75°; that of milo, about 70°. Sorghums are also widely used for forage, even well to the east in the cotton and the corn and winter wheat belts.

Cotton. About three fifths of the world's cotton comes from this country. Cotton is king in the cotton belt. Especially famous is the "sea-island cotton," which grows on the low sandy islands off the coast of South Carolina and Georgia, on the eastern border of the belt. The mean summer isotherm of 77° F. marks fairly closely the northern boundary, a mean autumn rainfall of 11 in. the southern boundary, and a mean annual rainfall of 23 in. (without irrigation) the western boundary of cotton production.[1] Both northern and southern boundaries are gradually moving northward, primarily because of economic conditions. Injury from the cotton-boll weevil, which is greater in the milder winter temperatures and the longer season near the Gulf, has resulted in higher prices. Cotton has therefore recently been increasingly produced in districts hitherto considered rather unfavorable. In spite of the lower yield in these northern fields, competition with the growers in the cotton belt proper, where per acre production has been greatly lessened by weevil damage, has proved profitable. The average length of the growing (frostless) season is two hundred days and in four fifths of the years is more than one hundred and sixty-five days. Warm and moderately moist weather is most favorable from April to August, and cool and dry autumns improve the quality and facilitate the picking. Autumn is in general the season of least rainfall in the cotton belt, which is a very favorable climatic feature. Too much rain in the picking-season injures the lint. An important climatic element in cotton-picking is the way in which the spells of dry weather are grouped. Rainless spells of three or four or more successive days are essential. Picking begins about August 10 in the southern and about September 10 in the northern part of the cotton belt. The seasonal migration of planting, from south to north, is at the rate of from ten to twenty miles a day. An important economic condition in connection with cotton is the fact that this crop requires labor throughout practically the whole year. Other less profitable crops therefore receive relatively little attention. In the

[1] O. C. Stine and O. E. Baker, Cotton section of *Atlas of American Agriculture*, Part V, Section A, 1918.

long hot summers of the southwestern corner of the arid interior, in southern Arizona and in southeastern California, a good deal of Egyptian cotton is grown under irrigation.

The dominance of cotton in the South has had many consequences of historical and economic significance. Its cultivation on hot, damp, often malarial lowlands led to the importation and employment of negro labor. In the cultivation, packing, and shipping of cotton, in its manufacture, and in the preparation of its by-products, enormous numbers of persons are employed. In the beginning New England, with its early industrial development, its high humidity, and the water power due to its abundant precipitation and rugged topography, was the center of cotton manufacturing. In recent years there has been a rapid increase of cotton mills in the South, along the Atlantic seaboard, where a large amount of water power is available. Dependence upon natural atmospheric humidity has been overcome by producing artificial moisture conditions. In the South the inroads of the cotton-boll weevil have led to a newly awakened interest in live stock and to a greatly increased acreage of velvet beans, used for forage.

Wheat. About three quarters of the winter wheat crop of the country comes from the corn and winter wheat belt and from the southern and eastern part of the corn belt. In the corn and winter wheat belt the usual crop rotation is corn, winter wheat, or oats and hay for one or two years. The isotherm of 72° for the month before harvest (June 15) marks fairly well the southern boundary of winter wheat. The mean winter isotherm of 20° is a general limiting control on the north. Wheat, on the whole, needs about the same amount of rainfall as corn. Between 15 and 30 in. are found where the wheat production is densest. Some wheat is, however, grown where the mean annual rainfall is 10 in. or even less, provided enough rain comes in the growing season. The critical month as regards rainfall in the case of corn is July, and March precipitation seems to be the most important for winter wheat. Thus it is seen that cold winters and dry springs are limiting controls of winter wheat.

More than about 45 in. is an excessive mean annual rainfall

for winter wheat. Toward the southern border of the corn and winter wheat belt the heavier rainfall causes rust, and early-maturing varieties of wheat are therefore planted in that section. Investigations made by the Department of Agriculture have shown that a difference of a week in the time of the harvest may mean a decrease of from ten to twelve bushels an acre in the yield.[1] Other reasons also prevent the raising of wheat south of the winter wheat belt. The mild winters may cause the growth of the plant before the late frosts are over, rains occur frequently during the harvest season, and there is the competition with cotton. Wheat and cotton both need labor at the same time. Wheat must be sown in the early fall, at cotton-picking time, and must be harvested in early summer when the cotton is being thinned. The Northeast, with its small fields, poor soil, and rugged topography, cannot raise wheat in competition with the West.

Spring wheat practically all comes from the spring wheat area and from the adjacent Great Plains region. Some also comes from the sub-humid portions of Washington and Oregon. The seed is planted in April, and harvesting comes in the latter part of July and in August. The rainfall conditions are not unlike in the winter and spring wheat provinces,[2] but the winters are colder in the latter. The northern boundary of winter wheat largely determines the southern boundary of the spring wheat area. A mean summer temperature of about 58° F. approximately determines the northern boundary of spring wheat. This isotherm is found in the mountain area of the West.

J. W. Smith has shown that the temperature of March is very critical for winter wheat, and that, in Ohio, at any rate, a snow cover seems to have no beneficial effect upon the winter wheat crop, nor is there any damage from the lack of such a cover, popular belief to the contrary notwithstanding.[3] It ap-

[1] A detailed map of the different wheat districts of North America may be found in the "Geography of the World's Agriculture," Fig. 12, p. 14. See also C. R. Ball and others, "Wheat Production and Marketing," *U. S. Dept. of Agric. Yearbook for 1921*, pp. 77–160.

[2] Spring-sown oats, barley, and wild hay are other important crops in the latter provinces.

[3] J. Warren Smith, "Agricultural Meteorology," *Proc. 2d Pan-Amer. Sci. Congr.*, Vol. II, Sect. II (1917), pp. 75–90 (discussion, pp. 90–92).

pears that bare ground with freezing and thawing weather in January is beneficial, and that snowfall in March is decidedly detrimental. The season of precipitation is important in other ways. Thus, on the Pacific coast, where the summers are relatively and in some sections even absolutely dry, methods of harvesting the grain and of leaving it outdoors without cover, which cannot be employed in the East, with its rainy summers, are practicable. Studies by crop experts of the Department of Agriculture have shown that climate has more influence than soil in determining the quality and the chemical composition of wheat, but that soil has a marked influence upon the permanency of wheat production in any given area. In California G. W. Shaw has shown, by experiments under shade, that the general effect of reducing the temperature was to increase the gluten content of the wheat.[1] The millers of that state have found it necessary to import considerable quantities of wheat in order to maintain the quality of their flour, owing to the low gluten content of the local wheat. The California valleys have too much sunshine for the best chemical composition of wheat.

The movement of wheat-growing in North America, as has been pointed out by Brigham, has been from east to west, and will be from south to north, following, both in direction and rate of movement, the development of transportation facilities.[2] Unstead believes that an enormous extension of the acreage of wheat into the more arid districts will occur, and that the yield per acre over lands now under cultivation will be increased by the application of the results of scientific investigation.[3] It is significant that in response to the distribution of wheat Minneapolis, in the spring wheat region, has the largest flour mills in the world, and that flour mills are located in all the larger cities along the Lakes and eastward to the coast.

[1] G. W. Shaw, "Climate and the Protein Content of Wheat," *Univ. Cal. Pub. Agric. Sci.*, Vol. 1, No. 5.

[2] A. P. Brigham, "The Development of Wheat Culture in North America," *Rep. Brit. Ass. Adv. Sci., 1909* (1910), pp. 230–246.

[3] J. F. Unstead, "The Climatic Limits of Wheat Cultivation, with Special Reference to North America," *Geogr. Journ.*, Vol. 39 (1912), pp. 347–366, 421–446.

Oats, Barley, and Rye. Oats are raised chiefly along the northern margin of the corn and winter wheat region, from New England to North Dakota, the area of maximum production being centered around the Great Lakes. There is a southwestward extension of the oat belt across eastern Kansas and Oklahoma to central Texas. Oats are of great value as a food crop for farm animals, and it is for this reason, rather than because of favorable climatic conditions, that this crop is largely raised in the corn belt and to the southwest of it. Since oats are sown (in the North) before corn, and ripen after it, the labor on the oat crop does not interfere at critical times with that required on corn. A cool, moist climate is best.[1] Both winter and spring oats are raised on the Pacific coast.

Barley now comes mostly from the spring wheat region and from Wisconsin. In the far West California produces considerable amounts under dry-farming methods or with irrigation. The grain grows under a wide range of temperate conditions. It is found chiefly in cool, sunny climates. In the most important barley districts no month during the growing season has a mean temperature over 75°. In Colorado barley grows at altitudes of several thousand feet, with much lower temperatures and not infrequent frosts. In southeastern California barley is raised where the mean summer temperatures are over 90°. The chief barley regions of the country have somewhat less than 35 in. of rain a year. In California the mean annual rainfall is less than 10 in. The crop is there grown during winter.

Rye has relatively slight importance. It comes mostly from the states bordering the Great Lakes, in the hay and pasture province, and from the spring wheat area. Rye is also extending out onto the Great Plains. Where production is greatest the mean summer temperature is about 70° and the mean winter temperature over 15°. Rye in the Red River valley grows where the mean winter temperature is about zero.

Tobacco. Nearly 90 per cent of the tobacco acreage is in six states (Kentucky, North Carolina, Virginia, Tennessee, Ohio, South Carolina) in the eastern and southeastern portion of the

[1] See Fig. 40, p. 35, "Geography of the World's Agriculture."

corn and winter wheat belt. Tobacco-growing under cloth has recently developed a secondary center of production in southern New England. Artificial covers help to keep the temperature uniform, especially by checking nocturnal radiation, and also diminish evaporation from the leaves. There are also centers of production in southern Maryland and in southern Wisconsin.

Potatoes and Other Vegetables, and Truck-Farming. The vegetable crops differ greatly under varying conditions of soil, climate, and economic controls. Certain vegetables are pretty well localized. Sweet corn and green peas are cool climate crops and come mostly from eastern middle latitudes; tomatoes come from almost all parts of the country except the spring wheat, northern Great Plains, and arid intermountain Plateau districts; sweet potatoes come from where the average growing season is more than one hundred and seventy-five days and the mean summer temperature is over 72°. Potatoes do well in a climate with fairly cool summers. Partly for this reason they come chiefly from the hay and pasture region, a center of heavy production being the extreme northeastern corner of that province (Aroostook County, Maine). Another reason for the heavy potato production north of the corn belt is found in the fact that corn requires labor at the same time and gives a larger return.

In the area lying between New York City and Norfolk, Virginia, about one fifth of the commercial crop of vegetables is produced. Florida and southern Georgia raise about one third of the winter vegetables, and California also has important centers in the Sacramento, Stockton, and Los Angeles districts and in the Imperial Valley. It may also be noted that potatoes and other hardy vegetables that require cool climates are produced as winter crops in the extreme South and as spring and fall crops in middle latitudes in order to escape the unfavorable effects of the warm summer weather.

Economic factors which make expensive and intensive cultivation profitable are controlling conditions in truck-farming, much of which is carried on under irrigation. The most important climatic factor in the case of early vegetables is freedom from frost. In view of the expense of cultivation and the

perishable nature of the products, the cost and distance of transportation are critical factors. In recent years there has been a rapid development of hothouse market gardening in the districts surrounding the larger cities, especially of the North and East. This type of farming, which produces a highly artificial climate at greatly added expense, is profitable as long as the products can compete in quality and in price with the vegetables which are more cheaply grown outdoors at greater distances from market but have the cost of transportation and are liable to deterioration en route.

Fruits. Deciduous fruits are characteristic of the type of farming in the hay and pasture region. The Pacific coast also supplies large quantities. "Winter-killing" of the trees and injury to buds or fruit by late spring or early autumn frosts are limiting climatic controls. In the East rainfall furnishes the water; hence the trees are generally fairly widely distributed. In the West most of the important fruit districts are irrigated; hence the trees are highly localized. The importance of topography and of the tempering effects of bodies of water is clearly seen in the fact that many of the very best fruit districts are on protected valley slopes or near large bodies of water. The southern shores of Lakes Erie and Ontario and the lower peninsula of Michigan are especially favored climatically, and are famous districts for apples, peaches, pears, and grapes. The eastern section of Wisconsin, along the shore of Lake Michigan, is also a well-known fruit center. Apples are the leading fruit crop. They are chiefly concentrated in the hay and pasture region. Here the climate is cool, and the winters are less severe and more moist than in the continental interior. The climatic limits of extensive apple production in the East are between a mean summer temperature of 79° on the south, a mean winter temperature of 13° on the north, and a mean annual rainfall of 18 in. on the west. The acreage is, however, thin north of the mean winter isotherm of 20°. Dry and cold winter winds are distinctly unfavorable. The apple districts (irrigated) of Washington, Oregon, California, and Colorado are also well known.

Peaches are much more sensitive than apples to cold. There-

fore, with the exception of the lake districts above noted, this fruit is found chiefly in the cotton belt and in the corn and winter wheat belts. Central Georgia is famous as an early-peach district, the Lake Ontario belt in New York as a late-peach district, and California as a center for canning and drying peaches. The mean winter isotherm of 25° is a fairly well-defined northern limit for extensive peach production, but the winter minimum is doubtless a more critical control than the winter mean. Cold dry winters are unfavorable. Important peach centers are also found in central California, in the Yakima valley of Washington, and in western Colorado. Warm protected valleys are favorite locations for peach orchards. Eastern pears come mostly from the Ontario shore belt, from the Hudson valley of New York, and from southwestern Michigan along the lake. In Wisconsin and Iowa the northern limit of pears follows the winter isotherm of 20° fairly closely. Western pear districts are the foothills of central and southern California, western Oregon, and eastern Washington (Yakima valley). Plums and prunes have their center of maximum production in central California. The Mediterranean climate of California is also wonderfully well adapted to the growth of European varieties of grapes, which, under the peculiarly favorable conditions of abundant sunshine and dry summers, are readily sun-dried for raisins.[1] About two thirds of the grape acreage is in California. Native varieties of grapes are characteristic of the East. The most striking concentration is in a narrow belt along the shore of Lake Erie, between Toledo, Ohio, and Buffalo, New York—the famous Chautauqua grape belt. Cherries are distributed through the corn and winter wheat belt, and are found locally farther north, where a mean winter temperature of about 16° seems to limit them. Olives are cultivated to a considerable extent on the foothills of southern California, where the dry summers and relative immunity from frost are peculiarly favorable. The chief cantaloupe districts are in the West, and are irrigated, whereas watermelons come from the South. Citrus fruits,

[1] See C. C. Colby, "The California Raisin Industry—A Study in Geographic Interpretation," *Annals Assoc. Amer. Geogr.*, Vol. 14 (1924), pp. 49–108.

which are very sensitive to frost, are practically limited to Florida and southern California.

The importance and wide distribution of these fruits have developed extensive canning and preserving industries. The shipment of fresh fruits, in heated or refrigerated cars, is a highly specialized part of the transportation problem. The western fresh-fruit industry is so important that at certain times "solid" refrigerator fruit trains are run through from the Pacific to the Atlantic coast.

Live Stock. Many factors, economic as well as climatic, control the distribution of cattle and swine. Both in the kind of live stock and in its management there are differences between East and West. Over the great fields of the semi-arid West the animals mostly graze on the open ranges without shelter. In the East much feeding is done in barnyards, and shelter is provided for winter. Swine come mostly from the East, sheep from the West. The better-watered portions of the West support cattle. Sheep are pastured in the drier sections. The eastern beef-cattle industry is chiefly centered in the corn belt, because of the availability of corn for feed, and of pasture. The Great Plains have about as many beef cattle as the corn belt, and the numbers are also fairly large in the sub-tropical coast and in the southern part of the cotton belt. It is not surprising to find a fairly close relation between the price of corn and that of beef. Corn and hay being cheaper in the states of the Middle West than farther east, the maximum concentration of beef cattle is in the western part of the corn belt and extends south through Oklahoma to Texas. The importance of the dairy industry and the increased need of fodder during the longer winters are additional factors limiting the numbers of beef cattle in the North and Northeast. The care of cattle in northern sections provides winter employment at a season when outdoor farming operations are at a standstill. In the South, on the other hand, the care of large numbers of cattle throughout the year would seriously conflict with the demand for outdoor labor, which is there never seriously interrupted by cold.

Swine come largely from the corn and winter wheat belt and from the cotton belt. They are also profitably raised in the

dairying districts, where skimmed milk, together with barley, corn, and mill feed, provides a good food supply. Horses are found in greatest numbers in the corn belt, and mules are raised chiefly in the corn and winter wheat belts. In both cases food is abundant, and farm and draft animals are needed on the farms. Mules are also widely used in the cotton belt.

In the West, especially on the treeless Great Plains, cattle are plentiful on the open ranges; but, as already noted, additional feed, such as alfalfa and other forage crops, and corn for final fattening, is being provided in increasing quantities. The milder winters and the less frequent and less severe storms of the southern portion of the Plains are an obvious advantage if cattle are unsheltered. Chiefly on account of the lack of feed, swine are not extensively raised in the Great Plains, Rocky Mountain, and arid interior districts. Sheep, on the other hand, are able to secure sufficient pasturage where deficient rainfall or a rugged topography does not provide favorable conditions for cattle. Most of the sheep are found in the Rocky Mountain states, where the mean annual rainfall is between 10 and 15 in. Where the rainfall is much less than 10 in. large numbers of sheep can no longer find enough pasturage. As winter comes on there is considerable migration of sheep from the higher mountain slopes to the lower valleys and to the open country. As in the case of cattle, the southern sections provide more favorable, because less severe, winter conditions.[1]

The live-stock interests give employment to vast numbers. The Chicago stockyards and the great packing and canning establishments for beef and pork products in Chicago, Kansas City, Omaha, and other western cities are known the world over. The transportation business for fresh meat, in refrigerator cars, has grown to vast proportions, involving cold-storage warehouses, artificial ice plants, and also specially designed refrigerating plants on steamships for export overseas. Modern methods of refrigeration make the packing and shipping industries independent of season and latitude.

[1] D. A. Spencer and others, "The Sheep Industry," *U. S. Dept. of Agric. Yearbook for 1923*, pp. 229–310.

Dairying. The hay and pasture region and the neighboring northern and eastern margins of the corn belt are the chief centers of the dairying industry. Dominant controls are obviously the abundance of summer pasture and of hay for winter-feeding, the proximity of city markets, which insures a large demand, and the quick and easy shipment of the perishable dairy products. The North Pacific Province, which has a cool and moist climate, is another important dairying section. Cool summers favor the production of high-grade dairy products, since the quality of the milk is more uniform and better than in the districts with higher temperatures. There are, for example, few cheese factories south of the mean summer isotherm of 70° F.

The Sub-tropical Coast Agricultural Region. The wide range of farming types along the southern coast makes it impossible to designate this province by any name expressing the dominant farming type. An important center of the citrus-fruit industry (oranges and grapefruit) is on the Florida peninsula. Orange plantations are also scattered through this province westward of Florida. The abundant rainfall of this section provides a sufficient and natural water supply for this valuable crop, but severe cold waves occasionally cause serious losses. There has recently been a rapid development of the satsuma industry in the eastern Gulf states, where many thousands of acres have been planted. The relative hardiness of this variety of orange is its great recommendation. The citrus-fruit industry of California is referred to in a later paragraph. Sugar cane raised commercially for sugar comes almost entirely from the lower delta of the Mississippi River, in Louisiana, where the rainfall is heavy (50–65 in.), and destructively low temperatures are rare. Sugar beets, on the other hand, come from the northwestern margin of the corn and winter wheat belt and from local areas in the West, especially Colorado and southern California. Profitable use of beets for sugar is on the whole limited to regions whose mean summer temperatures are below 72°. More than three quarters of the rice raised in the United States grows on the warm and well-watered coastal plains of Louisiana and Texas, in the western half of the Southern

Coast Province. The oldest rice district is on the protected tidal deltas of the extreme northeastern corner of this province, reaching into the adjoining coastal strip of the cotton belt (the Carolinas and Georgia). In Louisiana, rice needs water amounting to 0.5 in. of rainfall daily for three months, or 45 in. The amount of rainfall during the growing season being about 20 in., the equivalent of 25 in. has to be supplied by irrigation. Water for irrigation is obtained from the river or, on the coastal plain, by pumping from wells and bayous. Rice is also grown in the prairie district of eastern Arkansas and in the Sacramento valley of California.

Dry Farming. Roughly west of the 100th meridian by far the greater part of the country, except the north Pacific coast, receives insufficient rainfall for agriculture of the eastern type, and dry farming becomes a dominant type of agricultural practice.[1] It is applied mainly to small grains and is most widely developed in the Great Plains and Rocky Mountain Provinces and in the great valley of California.

Dry farming is farming without irrigation where the rainfall is too small for successful agriculture unless this rainfall is cared for and conserved in a special and peculiar way. The problem is essentially climatic. It becomes also a problem of soil preparation and of the proper selection of seeds and crops. But given enough and well-distributed rainfall there would be no dry-farming problem. Breaking up the hard subsoil so as to give the rainwater a chance to penetrate; keeping a thin, loose mulch on the surface to check evaporation; plowing in the spring,[2] so that the stubble may hold the winter precipitation; cultivating immediately after the plowing; selecting crops which will ripen quickly, will come nearest to maturity during the rainy season, and which, being drought-resisting, can wait until rains come,[3]—these are some of the simple and

[1] Irrigated farming is considered in the following section. In connection with the general possibilities of dry farming, reference may be made to Griffith Taylor's "Agricultural Climatology of Australia," *Quart. Journ. Roy. Met. Soc.*, Vol. 46 (1920), pp. 331–355.

[2] This becomes fall plowing in districts of winter rains. Fall-sown cereals take nearly a year to ripen.

[3] The cue to this selection comes from the native grasses, which grow mostly in spring and which can wait for moisture.

essential methods in dry farming. Soil properly treated by these methods, under favorable conditions, is damp down to six to eight feet or even ten to twelve feet.

There are other problems for this region. There is the question of the permanence of dry farming. A steady succession of crops dries up the soil in a few years, whence arises the need of manuring and of cropping in alternate years. There is also the desirability of tree-planting, and thus of making the farms more homelike and attractive. Dry farming is of such a comparatively recent date that there are a good many questions concerning it which time alone can answer. One thing is certain. There is a pretty definite limit to the amount of land which can be irrigated. Water will not be available for any more. Land which can be irrigated is naturally worth a good deal more than that which cannot. Dry farms require a large area. Hence modern agricultural machinery is a necessity, and its use is greatly facilitated by the absence of irrigating ditches. The best advice which can be given to any farmer in this semi-arid country is: "Wherever you can irrigate, irrigate; if you cannot irrigate, dry farm." As to the lowest mean annual rainfall limits for profitable dry farming in the western United States, it is difficult to give an exact figure. Perhaps from 10 to 12 in. would be a fair estimate. Six or seven inches are needed in the period from just before planting to before maturity, but topography, winds, slope, soil, and other factors are important controls and warn us against attempting too close an estimate. Where the mean annual rainfall is over 15 in. dry farming is practiced only where the distribution of the rainfall through the year is unfavorable for the crops, or where evaporation is large. Further, the rains which are most useful in dry farming are not gentle drizzles but heavy showers, exactly such as are common in the West. Two years' rainfall may be necessary for the production of only one crop. An excellent statement of the general economic and climatic status of dry farming has been given by W. M. Davis in the following words:

It has not yet been tried through a long enough period to make sure that it is more than a precarious occupation, sometimes

profitable, occasionally disastrous; it is invited more by the low price of arid lands than by the certainty of crops; it can be best practiced by those who have enough hope or capital to survive one or two years of failure with two or three of success.

Irrigation. Irrigation is an expression of man's dissatisfaction with the amount or distribution of rainfall. It is initially and fundamentally a climatic problem. Throughout the more arid portions of the West irrigation has been widely introduced where soils, temperature, and topography are favorable, and where a sufficient water supply from lakes, rivers, or wells is available. The largest irrigation enterprises have been undertaken by the national government. In some sections practically all of the necessary water supply comes through irrigation; in others, irrigation is used at certain times only.

Where irrigation is practiced, a wide range of crops can be raised, determined by local conditions of climate, soil, topography, and demand. Hence any complete agricultural map of the United States shows the concentration in the irrigated areas of a considerable diversity of products. Irrigation means a high price of land, relatively small holdings, and a high degree of local coöperation. Being an expensive type of agriculture it is to a large extent dependent upon economic controls. Reference has been made in the preceding pages to many of the crops which are raised under irrigation in the West. The most important of these are fruits and alfalfa, grains and potatoes. The citrus-fruit industry of southern California is one of the most striking illustrations of the value of irrigation in a dry region whose general climate, soil, and topography are favorable for the growth of valuable crops. Many interesting and successful experiments have been tried in the irrigated districts of southern Arizona, where rice, cotton, and a great variety of fruits, including dates, are raised.

Conditions in the West have gradually settled down to a reasonable adjustment on the part of man to the available water supply. It is now clearly recognized that the water available for irrigation is very limited; for it is obvious that all the water used in irrigating must have fallen somewhere as

rain or snow, and precipitation over most of the far West is small at best. Most of the "Great American Desert," as it used to be called, must forever remain non-agricultural. But careful study of all possible sources of water supply will result in further extension of irrigation enterprises over limited districts which are today producing nothing but sagebrush and other natural types of arid-land vegetation. About one third of the United States proper has in the long run too little rainfall for profitable crop production under normal conditions of market prices, and, furthermore, cannot be irrigated. It has been estimated by Baker and Strong that, if all available sources of water supply were fully utilized, the potentially irrigable land in the West would amount to about double the present area of irrigated land.[1] It is to be noted, however, that the cost of construction of irrigation works increases as less and less favorable projects are developed. The cost of land under the ditch and ready for farming may exceed the demand at the prices quoted, at least for a time.

To a superficial observer of these western "deserts" it seems as if irrigation must completely and successfully solve man's agricultural problems. But here, as everywhere, the apparent solution of one problem gives rise to other new and unexpected problems. Nowhere is there lack of struggle. When the groundwater level rises as the result of irrigation it causes a deposit of alkaline salts on the surface. Thus the irrigated desert has in places become an alkaline desert. The irrigation canals are bordered by weeds. From these, seeds drop into the water and are distributed over the fields and through the orchards, giving rise to another new problem. Thus the eternal struggle of man against nature goes on in varying phases.

Forests. There is a close resemblance between the forest map of the United States and the map of mean annual rainfall. Forests are the natural surface cover of the East (where they have been extensively cleared for lumber and to make room for agriculture) and over the mountains of the Pacific slope,

[1] O. E. Baker and H. M. Strong, "Arable Land in the United States," *U.S. Dept. of Agric. Yearbook for 1918*. Reprinted as Separate No. 771 (1919), 11 pages.

especially in the northwest.[1] With the exception of strips of timber along the rivers in the better-watered sections, the Great Plains are treeless, as are the Rocky Mountain and arid interior provinces, except the higher, and therefore rainier, mountains and plateaus. The heavy rainfall of the North Pacific Province is favorable for the growth of dense and very valuable timber. "Oregon pine" has been used for ships' masts and spars all over the world. The famous redwoods of California grow in the narrow fog belt on the Coast Range north of San Francisco, within a few hundred feet of the sea level, and extend about five hundred miles north and south.

Between the treeless Great Plains and the well-watered and naturally forest-covered East, a transition region—the prairies—has alternating grasslands and woodlands. The treelessness of the prairies has been ascribed to unfavorable climate, to the fineness of the soil, to fire, and to other causes. The explanation is probably to be sought in a combination of causes. Where trees are planted, they usually do well. On the Plains deficient rainfall, strong and steady wind movement, and active evaporation are distinctly unfavorable features.

On the Pacific coast lumbering is a perennial occupation. In the northern forests of the eastern half of the country the winter snows are an important factor in facilitating the removal of the timber on sledges, and the spring freshets serve to "drive" the logs down to the sawmills or to the railroads for shipment. Lumbering, sawmills, factories for the production of furniture,

[1] In a little-known publication (*Guide for the Transcontinental Excursion of the American Geographical Society, 1912*) Professor W. M. Davis wrote as follows concerning the forests of the eastern United States: "All the Atlantic slope was covered with forest, rarely interrupted by treeless spaces, but not infrequently devastated by fires. The early settlers had to clear the land for their farms. The hilly uplands of the interior were the 'backwoods,' and daring spirits who penetrated them were the 'backwoodsmen' of the eighteenth century, the heroes of many a story of adventure. . . . The heavy labor of clearing the trees from the forested eastern slope finds its memorials in our forms of speech today. The stump of a tree formed a convenient platform for political orators in rural districts, and now a candidate for an office who makes a series of speeches before election day is said to 'stump the State.' Again, the arduous work of rolling logs demanded the aid of neighbors. 'If you will help me roll my logs today, I'll help roll yours tomorrow,' and from this 'log-rolling' has come to be the phrase to indicate the exchange of political favors, even in prairie States where no actual log-rolling was ever done."

wagons, barrels, agricultural implements, etc., give employment to great numbers of men. It is natural that these industries should mostly be located near the source of supply of the raw material, as in the case of the sawmills of Washington, Oregon, and Maine, the barrel factories of Minneapolis, Minnesota, the furniture factories of Grand Rapids, Michigan. The men who engage in lumbering during the winter in the northern sections are largely employed in farming during the summer. Raphael Zon, of the United States Forest Service, has drawn a map showing the probable use of land fifty years hence. It seems likely that a very considerable extension of farm land will occur in the East at the expense of land now forested but capable of producing crops. In the West, excepting certain areas on the Pacific coast, the forests will not be reduced, because the land there is not suitable for farming. Zon believes that in fifty years the area devoted to agriculture, instead of being about 20 per cent of the total, will be nearer 50 per cent. The western mountains will, on the whole, always remain chiefly a forest region.[1] Baker and Strong have estimated that the country will require a woodland area of at least 450,000,000 acres to supply a population of 150,000,000 people. Hence a good deal of potentially arable land will remain in forest.[2]

Crops and Business. Agricultural prosperity is the keynote of general prosperity. From the fields come food and much raw material needed by the non-agricultural classes. Good crops, at good prices, provide those who live on farms with the means to improve and enlarge their buildings and to purchase manufactured products, agricultural implements, automobiles, and many luxuries in which they could not otherwise indulge. More work and larger profits are thus provided for the rest of the population. Abundant crops mean heavy shipments by rail and steamship, both from and to the farms, thus bringing larger receipts to transportation interests and, by increasing

[1] R. Zon, "The Future Use of Land in the United States," *U. S. Dept. Agric. Div. Forest. Circular 159.*

[2] O. E. Baker and H. M. Strong, loc. cit. in footnote 1, page 495. See also J. A. Larsen, "Why Hardwoods do not Grow Naturally in the West," *M. W. R.*, Vol. 52 (1924), p. 218.

the demand for rolling stock and cargo space, stimulating the employment of large numbers of men. A good surplus from the year's crops, with a ready market and fair prices, means paying off mortgages, larger bank deposits, and more money available for all sorts of enterprises, new and old. It means more money for producer, transporter, merchant, and consumer. Good harvests are, in ordinary conditions, the most important factor in determining the industrial activity of the nation.

A striking investigation of the influence of rainfall on financial conditions and on political changes in the United States was made some years ago by Clayton.[1] It appears that every great commercial panic from 1837 to 1893 occurred in or closely followed a protracted period of deficient rainfall. Following these periods of financial depression, marked political changes took place, it being a popular characteristic to put the blame for "hard times" upon the party in power. On the other hand, times of marked business expansion were periods with rainfall above the average. A curious case was the panic of 1907, which, as shown by Clayton in a later study, was of short duration and coincided with but one year of deficient rainfall. It is pointed out that, while there has been this close relation between rainfall and business conditions, there have been periods of deficient rainfall without panics. In the complex of modern industrial activity many causes operate to stimulate or to retard business conditions. Rainfall variations, making themselves felt through the crops, are but one factor, albeit a very fundamental one. Crop and business conditions in other parts of the world react upon those in any single country. A world-wide study of rainfall and other controls is necessary before any definite conclusions can be reached.

A. P. Andrew has also noted the connection between the crop yield and business prosperity or decline, and has shown the special importance of a large export wheat crop upon gold imports, bank reserves, and transportation and industrial interests.[2] H. L. Moore has investigated rainfall cycles, of

[1] H. H. Clayton, "Influence of Rainfall on Commerce and Politics," *Pop. Sci. Month.*, Vol. 60 (1901), pp. 158–165.

[2] A. P. Andrew, "The Influence of the Crops upon Business in America," *Quart. Journ. Econ.*, Vol. 20 (1906), pp. 323–352.

thirty-three and of eight years, and crop cycles and concludes that "the law of the cycles of rainfall is the law of the cycles of crops and the law of economic cycles."[1] And Brückner has brought out a striking parallelism between the fluctuations of rainfall in the United States, acting through the crop yield, and the volume of immigration to this country.[2] "The stream of immigrants to the United States ebbs and flows with the oscillations of climate, which give it a rhythmical impulse. And not only is immigration to the United States controlled by climatic oscillations, but also the settlement of the Far West."

[1] H. L. Moore, "Economic Cycles: their Law and Cause," 1914; idem, "Generating Cycles Reflected in a Century of Prices," *Quart. Journ. Econ.*, Vol. 35 (1921), pp. 503–526; idem, "The Origin of the Eight-Year Generating Cycle," ibid., Vol. 36 (1921), pp. 1–29.

[2] E. Brückner, "The Settlement of the United States as controlled by Climate and Climatic Oscillations," *Memorial Vol. Transcont. Excursion of 1912, Amer. Geogr. Soc.* (1915), pp. 125–139.

CHAPTER XXIII

THE CLIMATES OF ALASKA[1]

LARGER GEOGRAPHIC FEATURES AND CLIMATIC CONTROLS · CLIMATIC SUBDIVISIONS · THE SOUTHEASTERN COAST · ALASKA PENINSULA AND ALEUTIAN ISLANDS · THE INTERIOR · THE ARCTIC SHORES

Larger Geographic Features and Climatic Controls. Alaska is of vast extent and has a varied topography. It embraces many climates. It is on this account that there has been widespread misconception regarding its present conditions and its future. The pessimistic views as to its economic importance which were current in the earlier years after its purchase by the United States later gave place to highly optimistic views, exaggerated beyond all bounds of reason. Today the truth is seen to lie between these extremes. There are climates suitable for agriculture within certain fairly well recognized limits. There are also vast stretches where nothing of any value can grow. There are lofty snow-covered mountains; dense forests; numerous glaciers; bleak, treeless shores; foggy and inhospitable islands; picturesque fiords; great interior lowlands, carpeted with grass and moss and sprinkled with wild flowers in summer, but snow-covered wastes in winter. There has been the lure of gold and of furs and of fisheries and of timber. There are the hordes of summer tourists, visiting a small section of the southern coast, and there

[1] See Cleveland Abbe, Jr., "The Climate of Alaska." Extract from *Professional Paper No. 45, U. S. Geological Survey*, 1906, pp. 133–200 (although the observations upon which this study is based are not so complete as those now available, the essential facts are fully presented). The latest discussion of Alaskan climates is by M. B. Summers, for many years meteorologist of the Weather Bureau at Juneau ("Some Features of the Climate of Alaska," *M. W. R.*, Vol. 52 (1924), pp. 493–496). The following description of Alaskan climates is based chiefly upon the reports of Abbe and Summers. Many short descriptive accounts of Alaskan climate and weather have appeared in various scientific and popular journals and books.

are the scattered Eskimo bands on the bleak Arctic shores. Truly, Alaska is a land of contrasts.

In the south Alaska reaches about the latitude of Liverpool, England. Its northernmost point is within 18° of the north pole. The warm Pacific tempers its southern coast. Bering Sea, cold and ice-covered over its northern portion for half the year, lies to the west of continental Alaska. Its Arctic shores are closed to navigation about three quarters of the time. Its interior is so extended that the climate of that region has distinctly continental characteristics. Only its southern coastal belt is exposed to the modified prevailing westerlies. The general wind régime depends on the seasonally varying controls of the North Pacific low, the North Pacific high, and the pressures over the North American continent itself. In winter, with the North Pacific cyclone well developed and central to the southwest, the dominant wind movement over continental Alaska is from northeast; in summer, with the North Pacific anticyclone well marked and occupying its northernmost position, and with general lower pressures over Bering Sea and the north, the dominant wind movement over much of Alaska tends to be southerly and southwesterly. Locally, under topographic and other controls, there are often wide variations from the highly generalized wind directions here noted. Thus, the Arctic shores have much easterly and northeasterly wind in the warmer months, with more westerly and northwesterly wind in the winter, and the prevailing winds as recorded at individual meteorological stations often show decided departures from the general system.

The Cordilleran ranges, which constitute a well-marked climatic divide, closely follow the Pacific coast; merge, as a large topographic feature, with the Alaska Mountains; then fade out through the Alaska Peninsula into the long line of the Aleutian Islands, stretching far to the westward. North of the complex of the southern Alaskan ranges, which locally rise to peaks of eighteen thousand feet and over, and again serve as a climatic divide, comes the great interior, a low and more or less broken plateau, drained by the Yukon River, the great natural artery of Alaska, open to navigation during the short

summer, and ice-bound, but serving as a sledging-route, during the rest of the year. North of this interior lowland or low plateau, another series of low ranges and mountains separates the Yukon watershed from the tundra bordering the Arctic Ocean. Other less important geographic features are the Alaska and Seward peninsulas and the coast and islands of Bering Sea.

Climatic Subdivisions. For purposes of general climatic description Alaska may be divided into four major provinces. These are (1) the narrow southern, or southeastern, coastal belt —mild, equable, and humid; (2) Alaska Peninsula and the Aleutian Islands — somewhat colder and with less precipitation, but still typically marine and equable; (3) the interior, including, with some modifications, the Bering Sea coast— essentially continental in character; (4) the Arctic lowlands or tundra —mean temperature of the warmest month below 50° (F.), long severe winters, a "desert" with deficient precipitation.

The Southeastern Coast. This is the most accessible and best-known part of Alaska. The coast is rugged and mountainous, fringed with islands and cut by deep and irregular fiords. With its snow-covered mountains, dense forests, numerous accessible glaciers and waterfalls, and smooth inland waters well adapted for coastwise navigation, this strip of Alaskan coast has naturally become a popular tourist resort during the summer months. Exposed to the same prevailing onshore winds from the Pacific, and sharing more or less the same cyclonic and anticyclonic controls, southernmost Alaska has much in common with the coast of Washington and Oregon.[1]

The late Henry Gannett wrote:[2]

> Take the well-known climate of San Francisco, with its dampness, fogs and cold sea winds; reduce the temperature 15 to 18 degrees and increase the dampness and fog in proportion, and you have a fair idea of the climate of the Alaska Pacific coast.

[1] In 1857 Blodget wrote: "At Sitka . . . the saturation is excessive, and the quantity of rain like that of Bergen, Norway" ("Climatology of the United States," p. 195).

[2] Henry Gannett, "The General Geography of Alaska," *Nat. Geogr. Mag.*, Vol. 12 (1901), p. 186. See also A. W. Greely, "Handbook of Alaska; its Resources, Products, and Attractions in 1924," 3d ed., 1925.

The southern and southeastern coast of Alaska has a typical west-coast climate in the prevailing westerlies. The immediate coast is remarkably temperate, especially in view of its fairly high latitudes. The mean annual temperatures are between 40° and 45°; inland, they are a few degrees lower because of the colder winters. Minima of zero may apparently occur anywhere, oftener in the north than in the south, and some winters may go by without any zero temperatures except at inland stations. Zero readings occur less than twice a year at Juneau, on the average, and less than once a year at Sitka. The absolute minimum thus far recorded at any station in the Alaska "Panhandle" is −36°, at Klukwan. The "Panhandle" covers southeastern Alaska to the eastward of the 141st meridian. Kenai, on the Kenai Peninsula, six hundred miles to the westward, has an absolute minimum of −46°. The January monthly means are within a few degrees of 32° and are thus not very different from those of Chicago and Boston, for example; the July and August means are about the same as the May means at Denver, Bismarck, Chicago, and Boston. An absolute maximum of 99° has been recorded at one station, but the maxima are generally well below that. The mean annual ranges average about 25°–30° on the coast. Places less exposed to marine influences, farther inland, naturally have colder winters, lower minima, and larger mean annual ranges (up to about 50°). Except in rare and local cases, in the shallower bays in the north, navigation is possible all the year in the tidewater channels.

All conditions favor heavy precipitation: moist winds, marked cyclonic activity, orographic controls. Offshoots from the permanent Bering Sea, or Aleutian, low affect the weather every few days. The annual rainfalls at exposed southern coast stations near sea level are in the neighborhood of 150 in. and probably exceed 100 in., with local exceptions, as far as the Kenai Peninsula, after which they decrease. The water power is almost unlimited. The maximum amounts, falling on steep mountain slopes, are surely not yet recorded. In sheltered locations, back from the coast, the amounts are very much smaller, even becoming reduced to what would be a

reasonable rainfall for a continental interior. Local topography is here a marked control of rainfall. The marine type of rainfall distribution is dominant, the maximum coming in autumn and winter. "Long, incessant rains and drizzle" characterize the autumn and early winter months on the exposed coast. There is excessive dampness and much cloud and fog then. Sitka has an average of 83 days with a measurable quantity of precipitation during the 122 days from September to December, and Ketchikan has an average of 94 such days. Even in summer there are frequent rains. This is the best season for tourists, because it has less rainfall, clearer skies, and is much less raw and damp than the winter. It is also generally free from the high winds that are frequent in the colder season. A well-known guidebook cautions summer tourists to take warm clothing for use at night on the coast steamers, "though the sun may be quite powerful during the day." Thunderstorms are rare and generally of slight intensity. The growing season in the inlets and on the islands of the southern coast averages about two hundred days, decreasing northward. The snowfall varies greatly in depth according to local conditions, and in different years. At Sitka the mean annual amount is about 50 in.; at Cordova, 150 in.; on the east side of Kodiak Island, about 50 in. On the higher mountain slopes it is very deep, and adds much to the scenic attractions of the region. Climatic conditions are ideal for the development of glaciers, many of which are easily accessible by means of the tourist steamers. These sail up to the head of several fiords where some of the well-known glaciers end, and where icebergs and ice-floes may be seen in abundance. Farther north, not visited by the ordinary traveler, the glaciers are even larger and more numerous. The famous Malaspina Glacier, on the slopes of Mt. St. Elias, is one of the best known. The dense forest growth, which covers the lower mountain flanks in southeastern Alaska and stretches northward along the coast as far as Kodiak Island, is a great scenic attraction as well as a very valuable economic asset. A wonderful luxuriance of vegetation is favored by the equable temperatures and the heavy rainfall. Massive forest trees, with an abundance of smaller shrubs, berries, ferns, and

mosses, grow in the spongy soil. As is usual in similar natural regions elsewhere, lumbering and fishing are the dominant occupations.[1] Agriculture is carried on in certain selected localities, but the opportunities are limited. In summer, frost is practically unknown except, of course, at elevated stations and in the north.

Alaska Peninsula and Aleutian Islands. There is a gradual but no marked change in climate as one travels northward and then westward and southwestward along the coast, past the Alaska Peninsula, and down the long chain of the Aleutian Islands. The mean annual temperatures decrease; the summers become cooler, and the climate more equable; the rainfall is less than on the southeastern coast (60–80 in.); fog, cloud, the number of rainy days, and the wind movement increase; the growing season shortens. The climate is essentially dull, damp, chilly, with a constant succession of storms. Of Unalaska it has been said that the number of clear days in a whole year can be counted on the fingers of two hands. This statement is, however, not to be taken literally. Dutch Harbor, less than a mile from Unalaska, has an average of fifty clear days a year. Under special topographic controls and conditions of exposure, local climates may develop quite different conditions. Thus, in the Cook Inlet region, near the base of the Alaska Peninsula, which reaches well inland from the coast, a marked increase in temperature range, with less rainfall and less cloud, is noted. In contrast with the forests of the southeast, this western extension of the coast line is treeless, but has a heavy carpet of luxuriant natural grass.

The Interior. The winters are typically continental: long and severe. Snow covers the ground; minima of below −70° have been recorded; the monthly mean temperatures are a few degrees above and even well below zero, according to the locality, but temperatures below zero seldom persist for as long

[1] The native Indian tribes living on the exposed seacoast, finding land travel difficult, have become seafaring people. Spending most of their time in canoes, their arms, shoulders, and chests have become well developed, while the lower portions of their bodies are stunted. Thus, when employed as packers on the Yukon Trail, they proved unfit, as they were unaccustomed to walking and climbing (Ellen C. Semple, *Journ. School Geogr.*, Vol. 2 (1898), pp. 206–215).

as a month without a break. The cold is a "dry" cold, like that of the northern Plains in the United States, and is therefore not so bitter as the thermometer readings alone seem to suggest. Travel is by dog-sledge, and becomes difficult and even dangerous in high storm winds, but these are infrequent. The coldest weather in winter is calm and clear. Cyclonic disturbances are much less frequent in the interior than on the coasts. When an occasional depression moves northeastward across Bering Sea, the Seward Peninsula, and the Arctic region, southerly winds blow over the continental area of Alaska, usually with light to moderate snowfall and a rise in temperature.

With the sun climbing higher in the sky, and with the long hours of sunshine and of daylight, summer advances with astonishing rapidity. The snow usually disappears from the open lowlands in late April or in early May. The ice in the Yukon breaks up in May,—a thrilling and awe-inspiring sight,—and then navigation is possible from June to September or October, the length of this period varying somewhat from year to year. Trees, shrubs, berries, grass, wild flowers, mosses, make rapid growth. All nature responds to the heat and light of the summer sun. Summer monthly mean temperatures run between 50° and slightly over 60°. Maxima of over 90° have been recorded. While frost may occur at any time, it is usually light, and there is generally, in the agricultural districts at least, a frostless period from about mid-June to mid-August. Even when the air temperature is uncomfortably high, permanently frozen ground may be found not far below the surface. A striking paragraph from W. H. Dall, long one of the leading authorities on Alaska, has often been quoted.[1] The conditions here described obviously do not last long.

> In midsummer on the upper Yukon the only relief from the intense heat, under which the vegetation attains an almost tropical luxuriance, is the brief space during which the sun hovers over the northern horizon and the voyageur in his canoe blesses the transient coolness of the midnight air.

[1] W. H. Dall, "Alaska and its Resources" (Boston, 1870), p. 437 (quoted by Abbe, loc. cit.).

The continental character of the interior climate is seen not only in the large absolute temperature ranges, from minima of −60° to −80° to maxima approaching 100°, but also in the small rainfall, decreasing from the coast toward the interior from about 25 in. to less than 10 in., in round numbers; the occurrence of a summer rainfall maximum with diurnal showers; the marked seasonal variability in temperature and precipitation; and, as compared with the coast, sunnier skies, much less fog, fewer and much less intense storms, and generally decreased wind velocity. Glaciers, which are so numerous in the mountainous district near the coast, where snowfall is heavy and the summers are relatively cool, are lacking in the interior, where precipitation is less and the heat of summer greater. The amounts of snowfall vary from about 3 feet to more than 8 feet, with greater depths at the higher levels. Mild thunderstorms occur in summer.

Thick moss covers much of the interior, with grass also, and forests along the waterways, although the trees are smaller than those on the southeastern coast. Away from the streams, on the lowlands, the forests are more open and economically unimportant. They stop at from 3000 to 3500 feet above sea level. Wild flowers are abundant in summer. The nature of the country and the lack of good roads have combined to make summer travel difficult. In addition, mosquitoes are often a veritable summer plague.

Much that was unduly optimistic has been written regarding the agricultural possibilities of the interior of Alaska. It is true that, while the growing season is short, there are many hours of sunshine, and all vegetation makes luxuriant and rapid growth. Hardy and early varieties of grain, garden vegetables, and certain small fruits are successfully raised where conditions in some of the important valleys are favorable, where the soil has been properly treated, and where there is a local demand for them. On southern slopes, even as far north as the Arctic circle, farm produce has been raised. But the growing season is short at best; frost may come at any time, and there is great variability in seasonal temperatures, in rainfall, and sunshine. While the Alaskan interior is able to pro-

duce most of the crops required for home consumption, it cannot compete with more favored regions in raising crops for export.[1]

The Bering Sea coast, much of it a low, barren tundra, is a transitional climatic province which has many features similar to those of the Arctic coast. In a very general discussion such as the present one it may perhaps best be considered as part of the interior climatic province, with which it also has a good deal in common. There are, however, some modifications. Rigorous Arctic winters, with minima somewhat above those of the interior, increasing in severity toward the north; mild summers, with mean temperatures not many degrees lower than those of Sitka and with less extreme maxima than those inland; precipitation much less than in the "Panhandle," decreasing to the north, but averaging somewhat heavier than in the interior (30–15 in.); a late summer and early autumn maximum,—these are some of the climatic characteristics which mark a transition between marine and continental types. Fogs, especially in summer, are frequent over the Bering Sea, as are also severe winter gales. Little is known regarding the amounts of snowfall. Nome, on the Seward Peninsula, has about 5 feet. The heaviest falls are thought to occur on the southern slopes of that area. The various islands have their own more marine climates, with heavier precipitation, more fog, and more rainy days. An interesting economic aspect of the cloudiness on the Pribilof Islands is connected with the killing of the fur seals. If the seals lie in the sun they become overheated, and their fur is of less value if they are killed at such times. Hence, slaughtering is undertaken on cloudy, and preferably on foggy, days. Of Seward Peninsula, on the north shore of Bering Sea, it has been said that it probably has "the worst

[1] On this point the late Alfred H. Brooks wrote as follows: "The best of Alaska's tillable lands are in a zone directly served by the Alaska Railroad. Within a hundred miles of this trunk line there are over five million acres of prospective agricultural land. How soon this will be utilized depends on the development of other industries, chiefly mining, which will draw a population to consume the products of the farm. Even now there is room for farmers in this region, for the present scant population is not yet supplied with all the food that could be drawn from local sources. On the other hand, the outlook for any export of farm crops is not now promising." (A. H. Brooks, "The Value of Alaska," *Geogr. Rev.*, Vol. 15 (1925), p. 36.)

climate in Alaska in late summer and early fall"—chilly, damp, and windy, with frequent cold rains.

The Arctic Shores. The tundra, bordering the Arctic Ocean, is buried under snow, and the shores are blocked with ice except in midsummer or in late summer and early autumn. Easterly or southerly winds are the best for keeping the shores ice-free, whereas northerly and westerly winds drive the pack landward. The winters are long, severe, dark, and inhospitable. Snow falls to depths of perhaps 4 feet or so and is packed by the high winds into solid drifts, yet the total annual precipitation is so small that the region is truly an Arctic "desert." The minima are higher than the most extreme ones observed in the interior. The summers are very short. The warmest month has a mean under 50°; the maxima are considerably below those inland; frost is likely at any time. The influence of the cold waters is seen in this lowering of the maxima and in a retardation of the time of greatest summer warmth beyond July. During the long daylight season the snow melts; the ground thaws down to a depth of a few inches, becoming soft and marshy; the lowly vegetation consisting of mosses and lichens and wild flowers, and of dwarfed trees in sheltered spots chiefly along the watercourses, has its short season of growth. Even in summer, clouds and fog and rain are common.

The tundra offers little to support life except reindeer moss. The sea has inevitably supplied most of the food. An interesting development of the past few decades has been the introduction of reindeer to supply both food and clothing for the native Eskimos. These animals have increased rapidly in numbers and have proved a very valuable acquisition.[1]

[1] Seymour Hadwin and L. J. Palmer, "Reindeer in Alaska," *U. S. Dept. of Agric. Bull. No. 1089*, 1922.

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